AD/A-001 628

VULNERABILITY ASSESSMENT OF JP-4 AND JP-8 UNDER VERTICAL GUNFIRE IMPACT CONDITIONS

Jon R. Manheim

Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

December 1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

ACCESSION for

NTIS	White Section	☑
DDC	Buff Section	☐
UNANNOUNCED		☐

JUSTIFICATION ....

BY ....

DISTRIBUTION/AVAILABILITY CODES

Dist.	AVAIL. and/or SPECIAL	
A		

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/25 November 1974 — 400

ib

UNCLASSIFIED
Security Classification

AD/A-001 628

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

VULNERABILITY ASSESSMENT OF JP-4 AND JP-8 UNDER VERTICAL GUNFIRE IMPACT CONDITIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report February 1970 through March 1971

5. AUTHOR(S) (First name, middle initial, last name)
Jon R. Manheim

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1973	88	6

8a. CONTRACT OR GRANT NO. b. PROJECT NO. 3048 c. Task Nr. 304807 d.	9a. ORIGINATOR'S REPORT NUMBER(S) AFAPL-TR-73-76 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for Public Release, Distribution Unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Aero Propulsion Laboratory (SF Wright-Patterson Air Force Base, Ohio 45433

13. ABSTRACT

This report presents results of tests conducted to determine effects of a fifty-caliber incendiary projectile penetrating vertically from the bottom into a partially-filled fuel tank. Fuel types investigated in this program are JP-4 (high volatility fuel) and JP-8 (low volatility fuel). This test program was carried out in two phases: (1) "non-equilibrium" tests conducted with a cylindrical tank to determine effects of fuel temperature, initial ullage pressure, tank volume, fuel depth, venting, etc. a (2) equilibrium tests conducted with various rectangular tank configurations to determine effects of initial fuel-air mass ratio of the ullage fuel-air mixtures on ignition and reaction over-pressures. Results of "non-equilibrium" tests showed that both JP-4 and JP-8 can be ignited over the temperature range of 10 to 130°F. Results also showed that reaction over-pressures resulting from JP-4 tests were generally higher than those from JP-8 tests. Increasing fuel depth and venting area tend to decrease reaction over-pressures. Results of tests conducted with equilibrium fuel-air mixtures indicated that mixtures with initial fuel-air mass ratios as low as .002 could be ignited. No ignition was observed in fuel-air mixtures with initial fuel-a mass ratios greater than 0.11.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gunfire						
Aviation Fuels						
Flammability Limits						
Fuel System Vulnerability						
Aircraft Safety						

UNCLASSIFIED
Security Classification

☆U.S.Government Printing Office: 1974 — 657-015/221

AFAPL-TR-73-76

VULNERABILITY ASSESSMENT OF JP-4 AND JP-8 UNDER VERTICAL GUNFIRE IMPACT CONDITIONS

Jon R. Manheim

FOREWORD

This report was prepared by Jon R. Manheim of the Fire Protection Branch, Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory (AFAPL/SFH). The work reported herein was performed under Project 3048, "Fuels, Lubrication, and Hazards", Task 304807, "Aerospace Vehicle Fire Protection".

This report covers research accomplished in-house from February 1970 to March 1971.

The author appreciates the assistance received from other personnel of the Air Force Aero Propulsion Laboratory, the Air Force Flight Dynamics Laboratory and other organizations at Wright-Patterson Air Force Base. Special thanks are given to the following individuals: Messrs. W. Hall, D. Foster, and J. Walick of AFAPL for their invaluable help in the execution of the experiments.

This report was submitted by the author May, 1972.

This technical report has been reviewed and is approved.

ROBERT G. CLODFELTER
Chief, Fire Protection Branch
Fuels and Lubrication Division

ABSTRACT

This report presents results of tests conducted to determine effects of a fifty-caliber incendiary projectile penetrating vertically from the bottom into a partially-filled fuel tank. Fuel types investigated in this program are JP-4 (high volatility fuel) and JP-8 (low volatility fuel). This test program was carried out in two phases: (1) "non-equilibrium" tests conducted with a cylindrical tank to determine effects of fuel temperature, initial ullage pressure, tank volume, fuel depth, venting, etc. and (2) equilibrium tests conducted with various rectangular tank configurations to determine effects of initial fuel-air mass ratio of the ullage fuel-air mixtures on ignition and reaction overpressures. Results of "non-equilibrium" tests showed that both JP-4 and JP-8 can be ignited over the temperature range of 10 to 130°F. Results also showed that reaction over-pressures resulting from JP-4 tests were generally higher than those from JP-8 tests. Increasing fuel depth and venting area tend to decrease reaction over-pressures. Results of tests conducted with equilibrium fuel-air mixtures indicated that mixtures with initial fuel-air mass ratios as low as .002 could be ignited. No ignition was observed in fuel-air mixtures with initial fuel-air mass ratios greater than 0.11.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTD)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTD)

LIST OF TABLES

LIST OF TABLES (CONTD)

SECTION I

INTRODUCTION

The principal objective of this program was to investigate effects of various "Vertical" impact parameters associated with incendiary rounds on the flammability characteristics of JP-4 and JP-8. As illustrated in Figure 1, when a partially filled fuel tank is penetrated by a projectile in a slant trajectory, fuel mists and sprays can be produced. Addition of such mists and sprays to the ullage results in a heterogeneous fuel-air mixture. Flammability properties of such mixtures are generally different from those of homogeneous equilibrium mixtures and cannot be readily characterized in terms of conventional fuel-air ratios. In the case of an incendiary round, activation of the round is highly probable, resulting in the generation of numerous ignition sources within the ullage. Thus, in assessing potential hazards associated with aircraft fuel tank explosion induced by gunfire, conventional flammability data obtained under equilibrium conditions cannot be used. Under incendiary impact conditions the probability of ignition and the extent of a fuel-air reaction for a given fuel type depend largely on the degree of incendiary activation and dispersion as well as the nature of fuel mists and sprays. This report presents the results of tests conducted to determine effects of those parameters which were considered principal factors governing incendiary activation and fuel mist-spray formation.

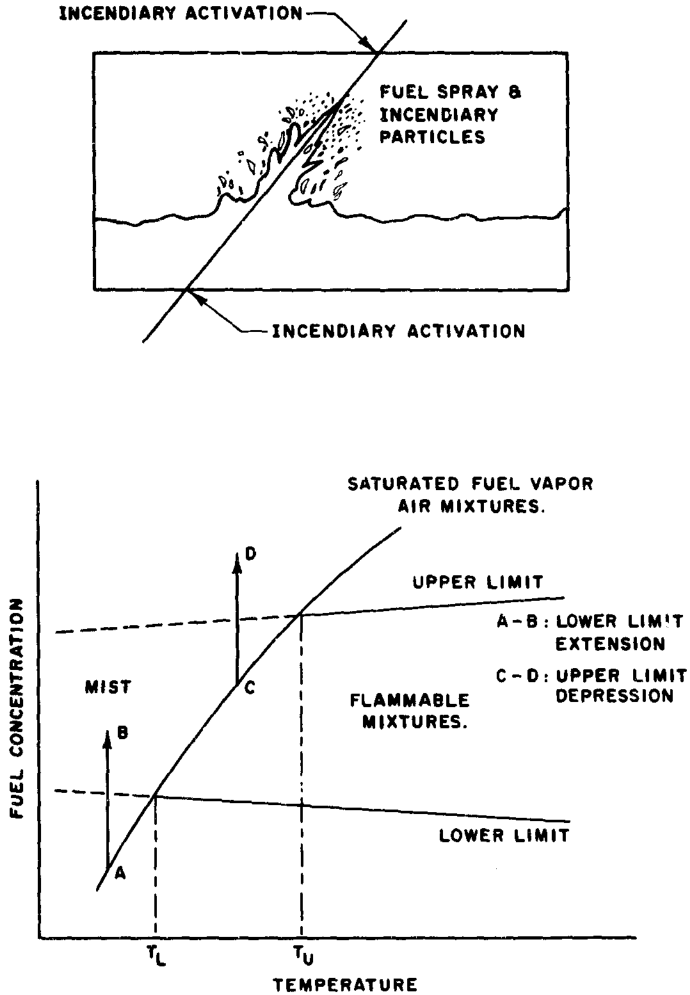

Figure 1. Effects of Vertical Gunfire Impact on Flammability Limits

SECTION II

EXPERIMENTAL EQUIPMENT

1. TEST FACILITY

All tests were conducted at the Air Force Flight Dynamics Laboratory's (AFFDL) Ballistic Impact Test Facility located at Wright-Patterson AFB, Ohio. This facility includes a semi-enclosed vertical firing tower and instrumentation trailers. The vertical tower has a provision for elevating a test article to an approximate height of 30 feet to provide the required vertical trajectory. Once elevated, the test article can be locked securely into the test firing position. The gun was located at the base of the tower and positioned to provide a 60° angle of elevation for projectile trajectory. Recording instrumentation and control equipment were housed in a trailer located near the vertical tower.

2. TEST EQUIPMENT

Tests were conducted using two types of tanks: cylindrical and rectangular tanks (Figures 2, 3, 4, and 5). The cylindrical tank was constructed from 3/8 in. thick stainless steel with tank dimensions as shown in Figure 6. The cylindrical tank consists of three sections: the main section with a capacity of 92 gallons and two identical extension sections giving a total capacity of 185 gallons when used with the main section. The rectangular tank, constructed from 1 in. thick steel plate, consists of five sections: the main section and four identical extension sections. The main section, measuring 36 in. wide, 36 in. long, and 18 in. high internally, has a capacity of 100 gallons (Figure 7). Each extension section, with internal dimensions of 36 in. wide, 18 in. long, and 18 in. high, has a fifty-gallon capacity. Both cylindrical and rectangular tanks were designed to withstand internal reaction over-pressures to assure a repeated use and both have identical provisions for control, instrumentation, and servicing.

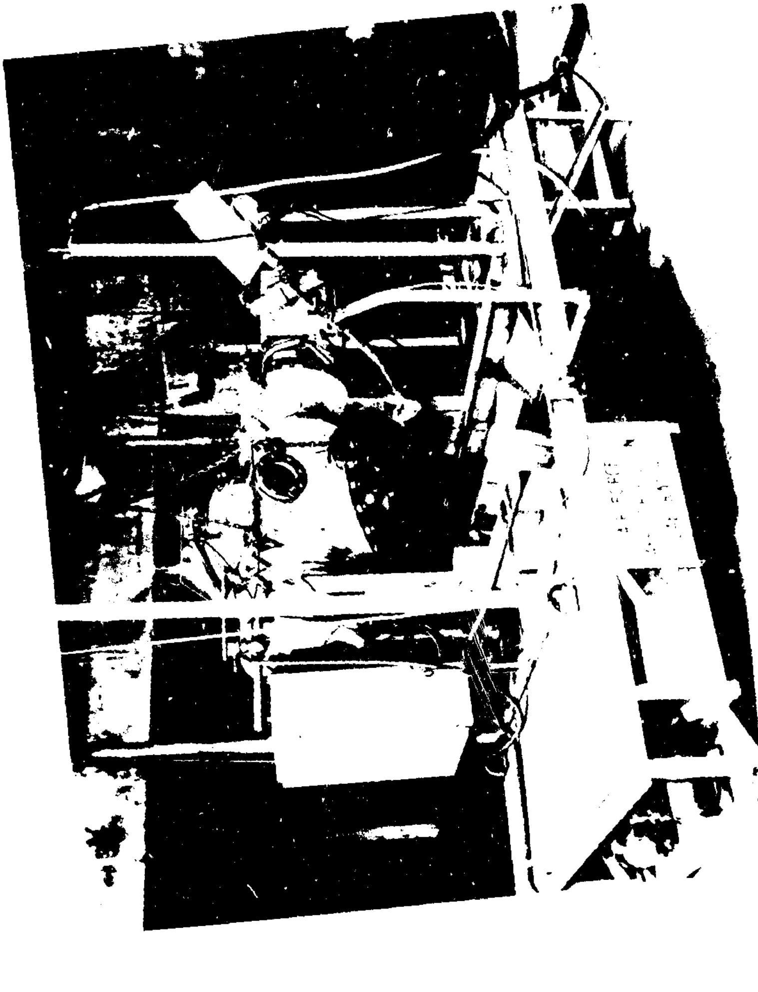

Figure 2. Cylindrical Tank - 90 Gallon Capacity

Figure 3. Rectangular Tank - Configuration A

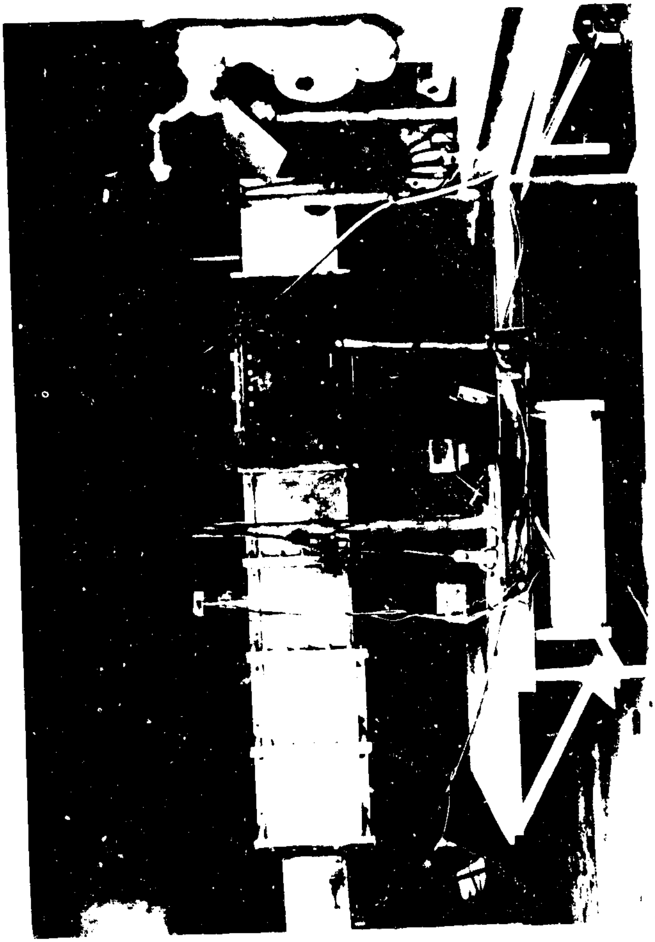

Figure 4. Rectangular Tank - Configuration C

Figure 5. Rectangular Tank - Configuration D. Also Shown are 50 Caliber Gun Mounted for 60° Angle Trajectory and Motion Picture Camera

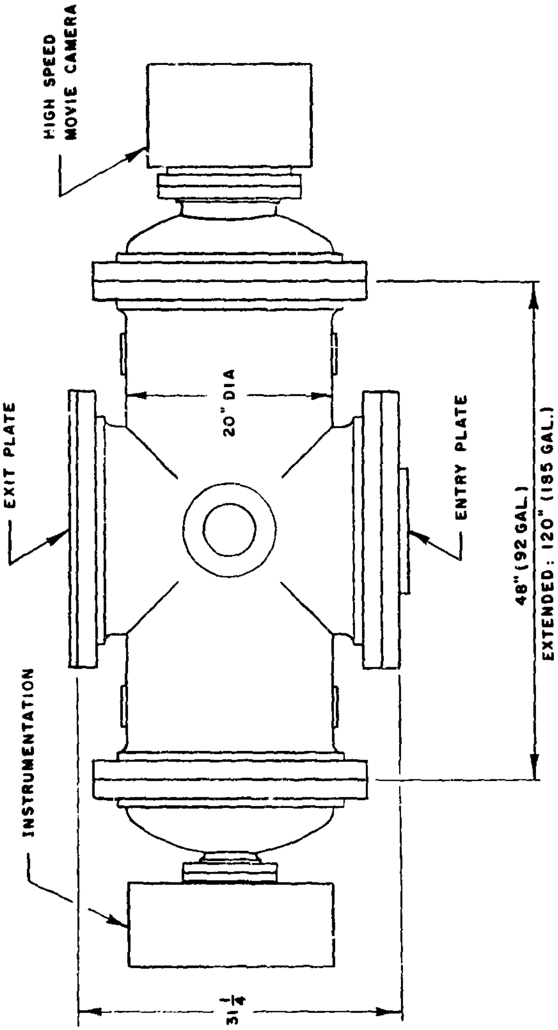

Figure 6. Cylindrical Tank - Top View

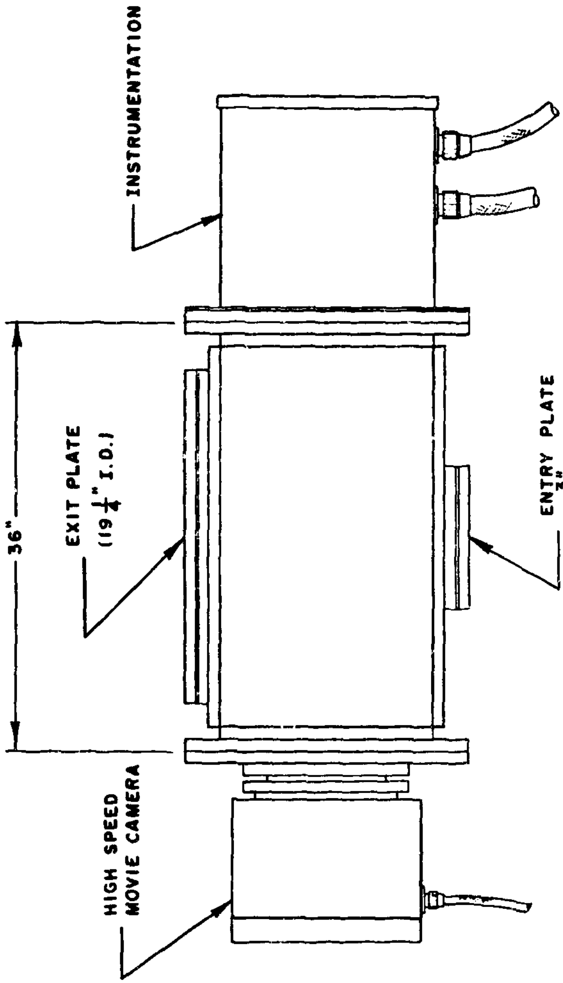

Figure 7. Rectangular Tank, Configuration A-Front View

Retainer rings were used for attaching entrance and exit plates. Entrance plates measuring 12 in. X 12 in. and exit plates measuring 28 in. X 28 in. were attached to the tank using 7.75 in. I.D. and 19.25 in. I.D. retainer rings respectively. An 8 in. diameter window was provided for motion picture coverage and a specially designed instrumentation port was used for introducing various instrumentation probes into the tank. For the purpose of obtaining fuel-air equilibrium within the ullage, fuel was circulated through a spraying tube with two rows of 1/16 in. diameter holes drilled 1/2 in. apart. The length of the tube, depending on the width of the test tank, was varied from 36 in. to 108 in. Heating of the tank was accomplished by means of hot air bath: heated air was blown into a specially designed canvas enclosure. Cooling of the tank was accomplished by circulating cold fuel.

A specially designed platform was used for mounting tanks. The cylindrical tank was mounted on this platform in such a way that the plane of entrance plate was a 90° angle with the trajectory. The rectangular tank was mounted to provide a 60° angle with the trajectory. The platform measuring 6 feet wide by 10 feet long has provisions for mounting two movie cameras, two fuel pumps, a vacuum pump, and two CO_2 fire extinguishing nozzles. In addition, it has a scrap fuel tank with a solenoid operated "trap door" mechanism to catch fuel leakage through a projectile entry hole. This arrangement minimized fire hazard by limiting external fuel fire to the vicinity of the test tank, where fire could be extinguished with the two CO_2 nozzles.

3. INSTRUMENTATION

a. Temperature Measurement

A total of eight thermocouples (copper-constantan, grounded junction) were provided for measuring tank surface, ullage, and fuel temperatures. Outputs from these thermocouples were recorded on a Brown recorder. Five chromel-alumel thermocouples with exposed junction made from 0.003 in. diameter wires were used to measure the fuel-air reaction temperatures at various locations of the ullage. Outputs from these thermocouples were on a seven-channel Offener recorder.

b. Pressure Measurements

The tank ullage and sample bottle pressures were monitored with two Wallace-Tiernan absolute pressure gages which were calibrated to read within ± 0.1 psi. Reaction pressures were measured using three strain-gage type transducers (CEC-4-311, 0-200 psia) and Brush 6 KHz carrier amplifiers. Pressure outputs were recorded on an eight-channel Brush oscillograph with high frequency galvanometers which have flat frequency characteristics to 1000 Hz.

c. Fuel vapor analysis

Four sampling probes were used to sample the fuel-air mixture at various points of the ullage. Sampling was accomplished by means of evacuated sample bottles which were kept at 4 to 5°F above the ullage temperature. These samples were then analyzed using a gas chromatograph (Varian 1520B) and ionization flame detector.

d. Motion picture coverage

A high speed (6200 frames/sec.) motion picture camera was used to record impact phenomena such as incendiary activation and fuel spray. Two additional cameras (64 frames/sec.) were used to record the events taking place at the entrance and exit plates.

SECTION III

TEST PROCEDURE

Test variables consisted of fuel type, fuel depth, fuel temperature, ullage condition, ullage pressure, tank geometry, tank volume, entrance and exit plate thickness, vent size, and projectile type.

The bulk of the tests were conducted with JP-4 (current Air Force jet fuel) and JP-8 (similar to commercial JET A-1). Typical inspection data along with calculated values of vapor pressure, molecular weight, and specific gravity for these fuels are given in the Appendix. In the course of testing, two different types of JP-8 were used: one with a nominal flash point temperature of 118°F and the other with 105°F. In addition, a limited number of tests were conducted with JP-5 (Navy fuel), jelled JP-8 (2 percent Dow Jelling Agent XD-7129.1), and propane.

In tests conducted with propane-air mixtures, a desired fuel-air ratio was obtained by first evacuating the test tank to approximately 6 psia and then adding a predetermined amount of propane. After these steps the ullage was pressurized with bottled air to a desired test pressure and then the ullage mixture was circulated internally to assure a complete mixing.

For regulating fuel temperature, fuel to be tested was conditioned separately from the test tank by either heating or cooling. For this purpose, fuel to be conditioned was placed in five-gallon containers which were then placed in either a heated canvas enclosure or an industrial freezer depending on the temperature desired. After the conditioning, the fuel was introduced into the tank in a measured quantity to provide a desired fuel depth. The fuel depth was measured along the trajectory as illustrated in Figures 8 and 9.

Fuel-air mixtures within the test ullage were regulated to produce either homogeneous equilibrium or nonequilibrium conditions. For tests conducted with equilibrium fuel-air mixtures, fuel was internally

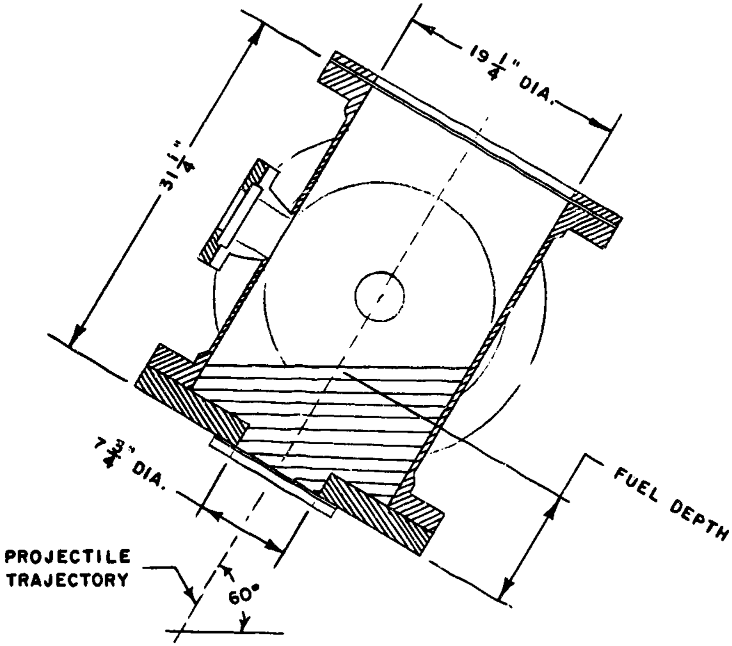

Figure 8. Cylindrical Tank - Sectional View

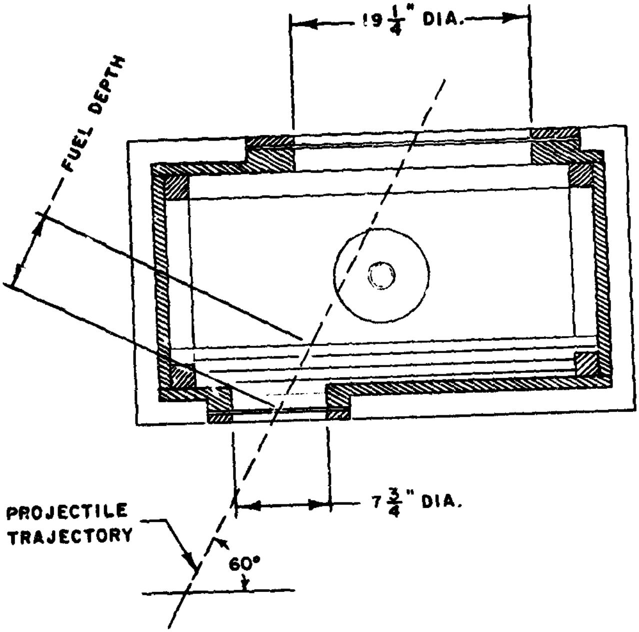

Figure 9. Rectangular Tank - Sectional View

circulated through a spraying bar for twenty minutes. For so-called "nonequilibrium" tests, the test fuel was allowed to rest in the tank for twenty to thirty minutes before the test firing was made. This waiting period was chosen to provide more uniform testing conditions for all nonequilibrium tests. If ullage samples were to be taken, they were taken at the end of circulation time or waiting period. Ullage pressures were regulated to produce 14.5 ± .3 psia for 1-atmosphere tests and 29.5 ± .3 psia for 2-atmosphere tests. Bottled air was used as a source for the ullage pressure.

For determining effects of fuel tank geometry and volume, two types of tanks were used; cylindrical and rectangular. The cylindrical tank was used in two basic volume configurations: one with a 92 gallon capacity and the other with a 185 gallon capacity. The rectangular tank was used in three volume configurations: 100, 200, and 300 gallons; however, by arranging the four extensions in groups of two, a total of five different configurations were obtained. These configurations are defined in Figure 10. Configurations D and E are identical except that E was separated into three equal volumes by means of two compartmenting plates. The plates were made from 1/4 in. thick aluminum sheet with fourteen 1 1/2 in. diameter holes arranged in two rows as shown in Figure 11.

With the exception of tests conducted to determine effects of entrance plate thickness, all other tests utilized 0.125 in. thick 2024 T-3 aluminum plates as entrance plates. 0.125 in. thick entrance plates when used with 4 in. fuel depth provided optimum condition for incendiary functioning at the central region of the test tank. Exit plates were standardized with 0.090 in. thick, 2024 T-3 aluminum plates.

In tests conducted to determine effects of venting, four vent sizes were used: 1, 2, 3 and 4 in. inside diameter. These vents were made

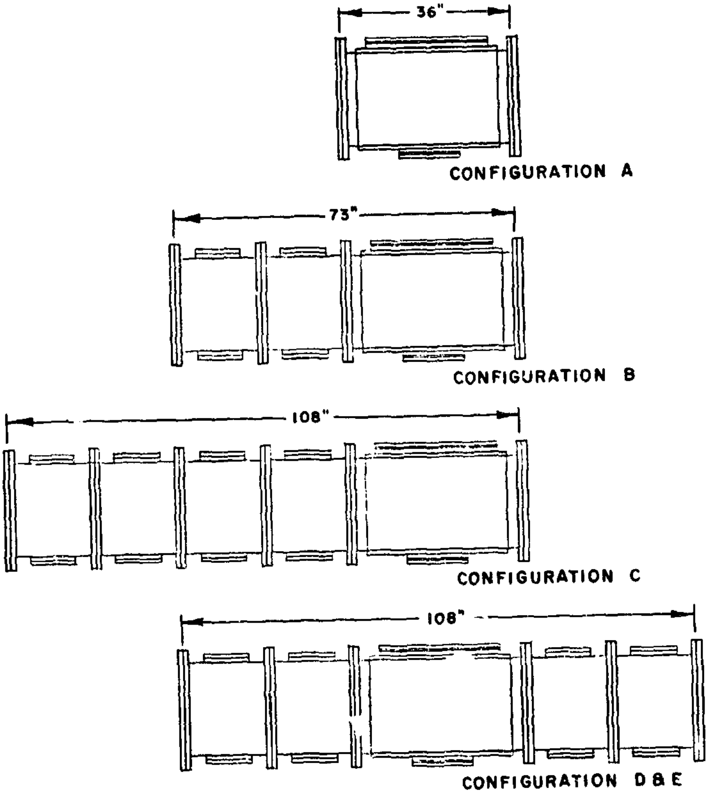

Figure 10. Rectangular Tank Configurations

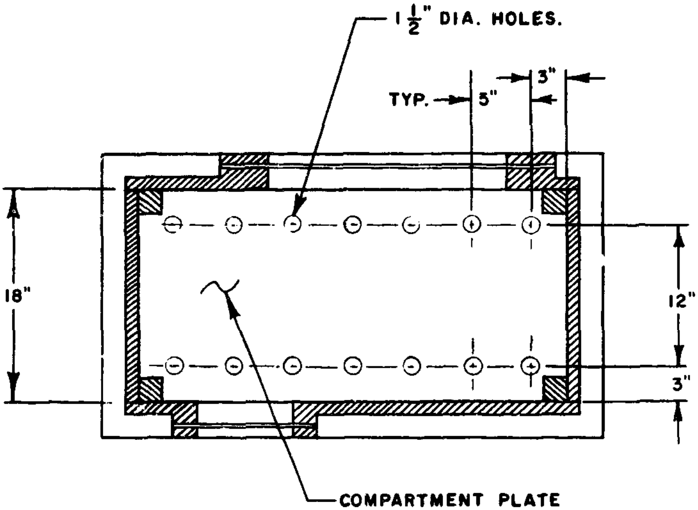

Figure 11. Sectional View of Rectangular Tank - Configuration E

from 12 in. long steel pipes and were equipped with valves to provide closed ullage during the required waiting or circulation period.

With the exception of eight tests conducted with 14.5 - 113.8 mm API, all other tests were conducted with 50 caliber API, type M-8 rounds. These rounds were fired at the service muzzle velocity of approximately 2800 ft./sec.

SECTION IV

TEST RESULTS AND DISCUSSION

The first part of the tests was conducted with the cylindrical tank to determine effects of fuel temperature, ullage pressure, tank volume, fuel depth, entrance plate thickness, and venting. A limited number of tests were also conducted using the cylindrical tank to investigate effects of "whiffle" balls, 14.5 - 113.8 mm API rounds, and jelled JP-8 on ignition and reaction over-pressures. With the exception of the "whiffle" ball tests, all other tests were conducted with nonequilibrium ullage fuel-air mixtures. The second part of the tests was conducted with the rectangular tank and equilibrium ullage fuel-air mixtures to determine effects of temperature, pressure, and tank configuration.

1. CYLINDRICAL TANK

a. Temperature Effects (Nonequilibrium Ullage)

Tests conducted to determine effects of fuel temperature are considered as standard tests and the following variables are identified as the standard test variables: four-inch fuel depth, 92 gallon tank capacity, 0.125 in. thick entrance plate, 0.090 in. thick exit plate, atmospheric ullage pressure, nonequilibrium ullage condition, and 50 caliber API at service velocity. Results of tests conducted with test variables other than those identified above were compared with the results of the standard tests.

Test temperature range was from 10 to 130°F. Results of tests conducted with JP-4 and JP-8 are summarized in Tables I and II, and mean values (ratio of reaction over-pressure (ΔP) to initial ullage pressure (P_I) with $\pm$ one standard deviation versus temperature are plotted in Figure 12. Data given in Table II include results from tests conducted with both 105°F and 118°F flash point JP-8 fuels, and for nonequilibrium tests, the small difference in the flash point temperature has no significant effect on observed results. Figure 13 shows typical pressure-time profile curves reproduced from original oscillograph records.

TABLE I

EFFECTS OF TEMPERATURE ON IGNITION
AND REACTION OVER-PRESSURE - JP-4

Temp. Range °F	Number of Tests	Number of Ignitions	Fractional Ignition	Standard Deviation	Mean ($\Delta P/P_I$)	Standard Deviation
10-19	5	2	.400	.2191	2.090	
30-39	6	3	.500	.2041	1.783	.3592
50-59	9	9	1.000	—	2.996	.6483
60-69	15	14	.933	.0644	3.4167	.6277
70-79	5	5	1.000	—	3.740	.6006
90-99	6	5	.833	.1521	3.658	.6[illegible]
110-119	5	3	.600	.2191	2.687	1.1254
120-130	5	1	.200	.1789	2.91 †	—

† Single Value

TABLE II

EFFECTS OF TEMPERATURE ON IGNITION
AND REACTION OVER-PRESSURE - JP-8

Temp. Range °F	Number of Tests	Number of Ignitions	Fractional Ignition	Standard Deviation	Mean ($\Delta P/P_I$)	Standard Deviation
10-19	5	2	.400	.2191	1.555	
30-39	9	3	.333	.1571	1.797	.7139
50-59	6	2	.333	.1925	1.850	
70-79	5	3	.600	.2191	2.000	.1646
90-99	17	14	.824	.0925	2.129	.3219
100-109	5	5	1.000	–	1.866	.5082
110-119	18	17	.957	.0475	2.208	.5807
120-131	12	11	.917	.0798	2.551	.4875

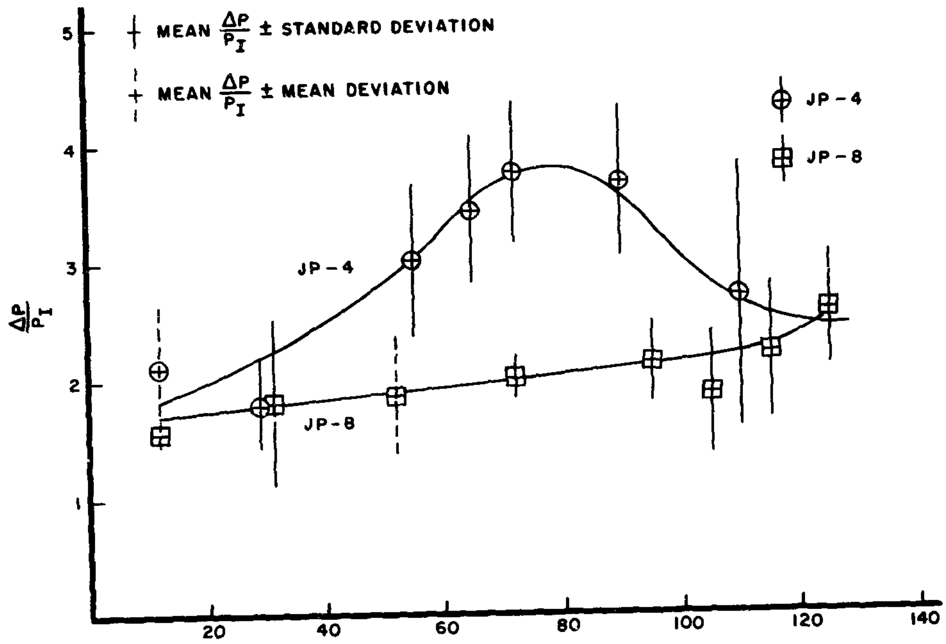

Figure 12. Effect of Fuel Temperature on Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8, Four-Inch Fuel Depth, and Atmospheric Ullage Pressure (92-Gallon Tank)

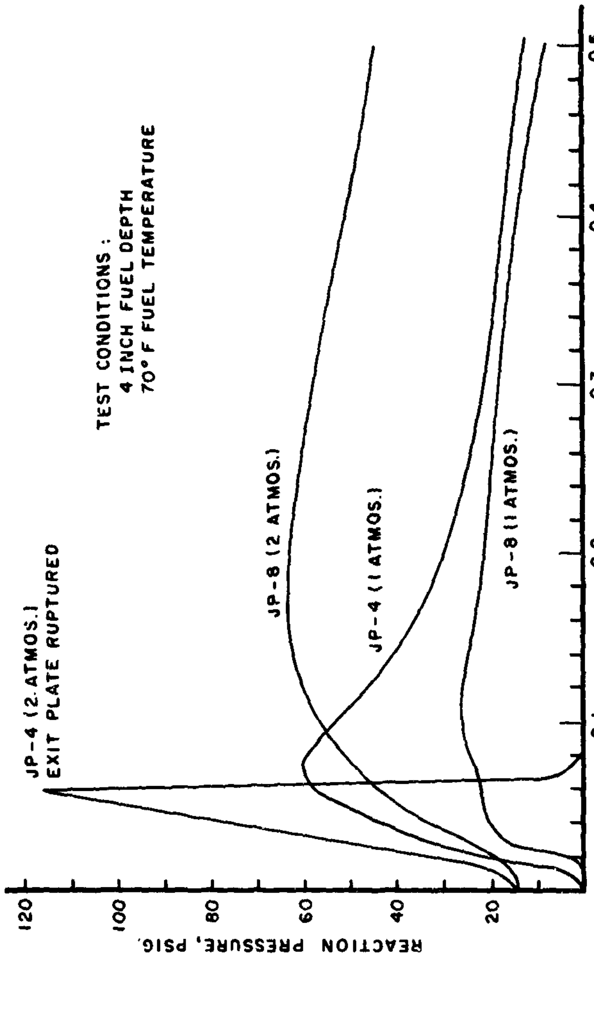

Figure 13. Typical Pressure-Time Profile

Inspection of the data shows that flammability limits - the upper temperature limit for JP-4 and the lower temperature limit for JP-8 - are significantly extended from those of equilibrium fuel-air vapor mixtures. In tests conducted with JP-8, ignition was observed at fuel temperatures as low as 10°F. At this temperature, the ullage equilibrium fuel-air mass ratio is in the order of 0.001 which is approximately one-thirtieth of that corresponding to the flash point temperature of JP-8. Thus, the ignition observed at such low temperatures represents a significant extension of the lower temperature limit of flammability. Analysis of high-speed motion picture film clearly indicates that such extension is due primarily to the impact-produced fuel mists and sprays.

In tests conducted with JP-4, ignition was observed at test temperatures as high as 130°F. However, this apparent extension of the upper temperature limit of flammability should not be considered as a gunfire impact effect for this extension is due mainly to the nonequilibrium fuel-air mixture conditions of the ullage. Under the nonequilibrium test conditions, the amount of fuel vapor in ullage is totally governed by the vaporization rate. Thus, the amount of fuel vaporized in a "waiting" period of 20 to 30 minutes is expected to increase with increasing fuel temperature; but because of the relatively short "waiting" period the amount of fuel vaporized at a given temperature is considerably less than the equilibrium fuel concentration corresponding to that temperature. This is evidenced by the ignition observed at the fuel temperature of 130°F which is well above the upper temperature limit of flammability for JP-4. Inspection of the test data given in Table I shows that the relative ignition frequency is low at temperatures below 40°F, high between the temperatures of 50 and 100°F, and low again above the temperature of 110°F. This behavior is directly attributable to the increasing fuel vapor concentration with the increasing fuel temperature and is similar to that of equilibrium fuel-air vapor mixtures over the approximate temperature range of 0 to 70°F.

For the purpose of comparison, 12 tests were conducted with JP-4 equilibrium fuel-air mixtures over the temperature range of 64 to 94°F. All other test variables remained as previously discussed. As shown in Table III, none of the tests resulted in ignition. Thus, it is evident that the extension of the upper temperature limit of flammability observed in nonequilibrium tests does not occur in equilibrium tests.

As evidenced by large values of standard deviation in mean values of $\Delta P/P_I$, there exists a considerable variation in reaction over-pressures over a small range of temperature. For example, over the temperature range of 90 to 99°F, $\Delta P/P_I$ resulting from JP-8 varied from 1.66 to 2.67 and over the same temperature range JP-4 $\Delta P/P_I$ varied from 2.90 to 4.39. This is probably due to the random nature of incendiary activation and fuel mist-spray formation, and some variation in fuel vapor concentration. Because of the large variations in $\Delta P/P_I$, it is very difficult to characterize any given test shot in terms of $\Delta P/P_I$. However, when mean values of $\Delta P/P_I$ are plotted as a function of temperature as in Figure 12 there appears to be a clear trend. For JP-4, $\Delta P/P_I$ increases with increasing temperature up to 80°F, and thereafter, decreases with increasing temperature. Here again, as in the case of ignition, this behavior can be attributed to the increasing fuel vapor concentration with increasing temperature. As seen in Figure 12, the shape of the plotted curve for JP-4 is very similar to that of the equilibrium fuel-air vapor mixtures. The only exception is that the plotted non-equilibrium curve is displaced upward in temperature.

For JP-8, $\Delta P/P_I$ increases very slowly with increasing fuel temperature over the temperature range of 10 to 120°F and a considerable increase thereafter. This nearly temperature independent nature of $\Delta P/P_I$ below the flash point temperature of JP-8 indicates that reactions taking place below the flash point temperature involve mainly impact-produced fuel mists and sprays.

TABLE III

EFFECTS OF EQUILIBRIUM FUEL-AIR MIXTURE ON IGNITION - JP-4

Test No.	Fuel Temp. °F	Initial Pressure psia	Fuel-Air Mass Ratio	Ignition
337	94	14.5	.466	No
338	94	14.5	.466	No
339	94	15.5	.431	No
340	91	15.5	.400	No
341	90	15.5	.395	No
342	90	15.4	.398	No
343	90	14.5	.427	No
344	64	15.1	.212	No
345	64	15.0	.213	No
346	65	15.0	.220	No
347	67	15.1	.229	No
348	67	15.1	.229	No

b. Effects of Two-Atmosphere Ullage Pressure (Nonequilibrium Ullage)

Results of tests conducted to determine effects of increased ullage pressure on ignition and reaction over-pressure for JP-4 and JP-8 are presented in Table IV. With the exception of increased ullage pressure, all test variables used in this test series are identical to those used in the standard test series.

All tests conducted with JP-4 resulted in a massive failure of exit plates; thus true maximum reaction over-pressures for these tests could not be determined. A ruptured exit plate is shown in Figure 14. Reaction over-pressures given in Table IV are those pressures at which exit plates were ruptured. This massive failure of the exit plate also created a severe fire hazard at the vicinity of the test article, thus necessitating a limit to the number of tests to be conducted with JP-4 to two tests each at 70°F and 110°F. Because of this limited number of tests an extensive analysis cannot be made. However, when compared with the results of JP-4 tests conducted with one atmosphere initial ullage pressure it becomes evident that increasing initial ullage pressure results in a substantial increase in reaction over-pressures.

Results of tests conducted with JP-8 show that both ignition and reaction over-pressure are not consistent. Out of 12 tests conducted with JP-8 only six resulted in ignition. Of those ignited, three tests resulted in reaction over-pressures comparable to those of 1 atmosphere tests and the other three considerably higher. In view of this inconsistent nature of the result, no meaningful conclusion, other than that increased ullage pressure can increase reaction over-pressures, can be made on the effects of increased ullage pressure.

c. Effects of Fuel Depth (Nonequilibrium Ullage)

This series of tests was conducted to determine effects of fuel depth on ignition and reaction over-pressures for JP-8 and JP-4. Results of tests conducted with JP-8 are summarized in Table V and mean values of

TABLE IV

EFFECTS OF TWO-ATMOSPHERE ULLAGE PRESSURE
ON IGNITION AND REACTION OVER-PRESSURE

Fuel Type	Test Number	Fuel Temp. °F	Initial Pressure psia	Reaction Pressure psi
JP-8	285	71	29.5	0
	286	70	29.6	48
	287	70	29.6	0
	288	68	29.5	0
	289	90	29.5	53
	290	93	29.5	0
	291	88	29.5	24
	292	90	29.4	47
	293	109	29.4	34
	294	110	29.5	39
	295	111	29.5	0
	296	109	29.4	0
JP-4	310	72	29.5	>101*
	328	66	29.5	>100*
	319	109	29.4	> 86*
	320	110	29.4	>108*

*Pressure at which exit plate ruptured

Figure 14. Comparison Between Ruptured and Non-Ruptured Exit Plates

TABLE V

EFFECTS OF FUEL DEPTH ON IGNITION AND REACTION OVER-PRESSURE - JP-8

Fuel Depth Inches	Number of Tests	Number of Ignition	Mean ($\Delta P/P_I$)	Standard Deviation
2	5	5	1.792	.3442
4	17	14	2.129	.3219
6	4	4	2.115	.2588
8	7	5	2.042	.4341
10	5	3	1.757	.1401
12	5	5	1.360	.4849
14	5	1	1.388*	–
16	5	1	1.110*	–

*Single value

$\Delta P/P_I$ along with $\pm$ standard deviations are plotted as a function of fuel depth in Figure 15. JP-4 results are given in Table VI. With the exception of fuel depth, all test variables used in this series of tests are identical to those used in the standard test series. Initial fuel temperature was kept constant at 95 $\pm$ 5°F and fuel depth was varied from 2 to 16 in. in increments of 2 in.

Inspection of JP-8 data given in Table V shows that increasing fuel depth from 2 to 12 in. has no significant effect on ignition. However, at 14 and 16 in. of fuel depth the percentage of ignition is reduced considerably. When mean values of $\Delta P/P_I$ are plotted against fuel depth, as in Figure 15, it becomes apparent that reaction over-pressures are largest between the fuel depth of 4 to 8 in. and decrease thereafter with increasing fuel depth. This is probably due to reduction of incendiary particles and fuel spray. Analysis of high speed motion picture film clearly indicates that both incendiary particles and fuel spray decrease with increasing fuel depth. It appears that incendiary particles activated at the entrance plate were partially quenched within the liquid medium and, as the fuel depth was increased, an increasing number of incendiary particles were quenched. At the fuel depth of 16 in. a near total quenching was observed, which is probably the cause for significant reduction in ignition at this fuel depth.

With the increasing fuel depth, a gradual reduction of fuel spray was observed. Since all tests were conducted with nonflammable (fuel-lean) fuel-air mixtures, the amount of fuel burned is totally governed by the amount of fuel spray produced. Thus, with reduction of fuel spray, reaction over-pressures are expected to decrease. At the fuel depth of 4 in., fuel spray produced by the impacting projectile was widely distributed within the ullage. However, when fuel depth was increased to 16 in., fuel spray was produced mainly along the projectile path. This may account for the 50 percent reduction in reaction over-pressure observed when the fuel depth was increased from 4 to 16 in.

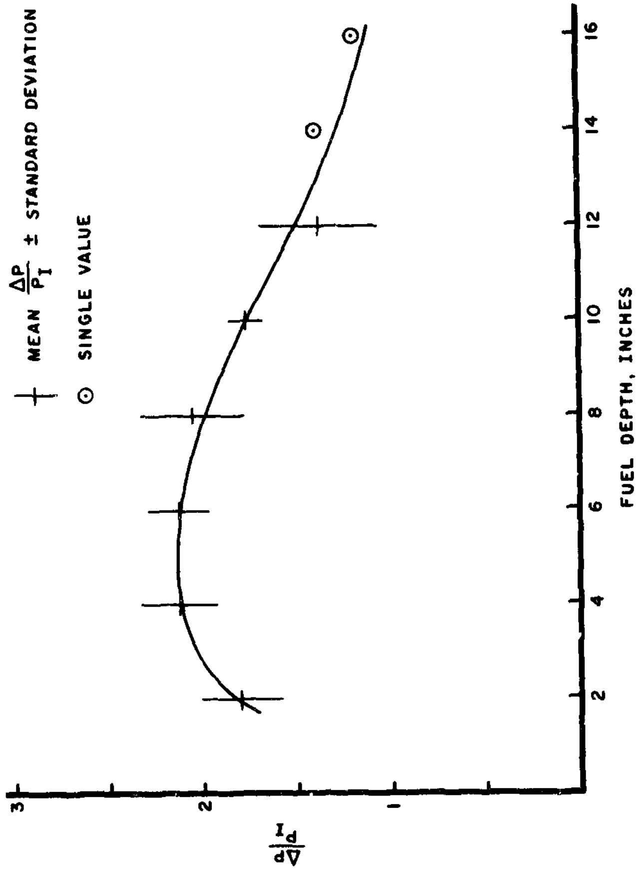

Figure 15. Effect of Fuel Depth on Reaction Over-Pressure in Tests Conducted with JP-8 at 95 ± 5°F and Atmospheric Ullage Pressure (92-Gallon Tank)

TABLE VI

EFFECTS OF FUEL DEPTH ON IGNITION AND REACTION OVER-PRESSURE - JP-4

Test Number	Fuel Depth Inches	Fuel Temp. °F	Initial Pressure psia	Reaction Pressure psi
132	2	30	14.7	32
151	2	64	14.4	21
133	6	30	14.7	0
141	6	34	14.3	40
153	6	61	14.4	46
417	6	89	14.5	0
420	6	90	14.5	0
134	8	30	14.7	29
154	8	62	14.4	0
159	8	62	14.4	0
404	8	91	14.5	0
405	8	88	14.5	0
406	8	88	14.5	0
407	8	88	14.5	0
408	8	88	14.5	0
415	8	89	14.5	0
416	8	88	14.5	0
418	8	92	14.5	0
419	8	90	14.5	0
421	8	92	29.4	84
422	8	92	29.4	0
135	10	30	14.7	28
155	10	60	14.4	32
409	12	90	14.5	0
410	12	87	14.5	0
411	12	88	14.5	0
412	12	86	14.5	0
413	12	90	14.5	0

Inspection of JP-4 data given in Table VI shows that none of the tests conducted with increased fuel depth at a constant temperature of ~ 90°F and pressure of 1 atmosphere resulted in ignition. However, when tests were conducted with either increased ullage pressure (2 atmospheres) or decreased fuel temperature (60°F), either of which leads to a lower fuel concentration, ignition did occur. When these results are compared with the results of tests conducted with 4 in. fuel depth, it becomes evident that increasing fuel depth has an effect of increasing fuel concentration. Since fuel spray decreases with increasing fuel depth it is believed that the increase in fuel concentration is entirely due to an increase in fuel vapor concentration. This can be explained if tank geometry is considered in conjunction with increasing fuel depth. The tank geometry is such that increasing fuel depth also increases surface area of the liquid fuel. The surface area corresponding to an 8 in. fuel depth is four to five times as large as that of 4 in. fuel depth. Since vaporization rate depends greatly on the surface area of the liquid fuel the amount of fuel vaporized in a given time from a larger surface area is expected to be greater than that from a smaller area. Thus, in the tests conducted with increased fuel depth and fuel temperature of ~ 90°F, evidently, a sufficient amount of fuel was vaporized during the "waiting" period of 20 to 30 minutes to cause fuel-air mixtures to become nonflammable (fuel-rich).

d. Effects of Increased Ullage Volume (Nonequilibrium Ullage)

This series of tests was conducted to determine effects of increased tank volume (185 gallon) on ignition and reaction over-pressures for JP-8 and JP-4. With the exception of the tank volume, all test variables used in this test series are identical to those used in the standard test series. Test temperatures were ~ 70, ~ 90, and ~ 110°F and ullage pressures were 1 and 2 atmospheres. Test results are presented in Table VII.

Comparison of JP-8 data given in Table VII with the results of the standard test series indicates that increasing ullage volume has no effect on ignition but has a significant effect on reaction over-pressures.

TABLE VII

EFFECTS OF INCREASED ULLAGE VOLUME ON IGNITION AND REACTION OVER-PRESSURES. JP-4 AND JP-8

Fuel Type	Test Temp. °F	Initial Pressure Atmospheres	Number of Tests	Number of Ignitions	Mean ($\Delta P/P_I$)	Standard Deviation
JP-8	70 ± 2	1	5	5	.806	.2775
"	90 ± 3	1	5	5	.998	.2826
"	109 ± 3	1	5	4	1.033	.1750
"	71 ± 2	2	5	4	.568	.0340
"	94 ± 3	2	5	3	1.130	.1709
"	110 ± 1	2	5	4	.755	.1777
JP-4	74 ± 3	1	5	4	3.910	.3529
"	92 ± 2	1	5	3	3.967	.4267
"	110 ± 2	1	5	5	4.110	.1210
"	74 ± 4	2	5	5	1.938	.3644
"	91	2	2	2	3.29* & 3.59*	Exit plate rupture
"	110	2	2	2	3.49* & 2.85*	*Single values only

Reaction over-pressures are approximately one-half of those observed in the standard test series. This is probably due to the fact that the amount of fuel spray produced is independent of tank size. A similar result was also observed in tests conducted with two atmosphere ullage pressure.

In tests conducted with JP-4 at one-atmosphere ullage pressure, reaction over-pressures were nearly constant over the temperature range of 70 to 110°F and ranged from a minimum of 51 psi to a maximum of 62 psi. When these results were compared with the results of the standard test series, reaction over-pressures observed at 70 and 90°F are comparable and at 110°F considerably higher. In order for this to occur, the amount of fuel combusted in the extended tank must be at least twice as much as that combusted in the standard tank. Under the test conditions, the amount of fuel vapor present in the ullage is approximately the same for both tanks; thus, it is seen that a greater part of the additional fuel combusted in the extended tank must be in the form of fuel mists and sprays.

In tests conducted with two-atmosphere ullage pressure and fuel temperature of ~ 74°F, no appreciable change in both ignition and reaction over-pressure was observed. However, when tests were conducted with the increased fuel temperature (91° and 110°F), all tests resulted in a massive failure of exit plates. This result is similar to that of tests conducted with the standard tank at two-atmosphere ullage pressure; thus, results discussed in that section can also be applied in this section.

e. Effects of Entrance Plate Thickness (Nonequilibrium Ullage)

This series of tests was conducted to determine effects of entrance plate thickness on ignition and reaction over-pressures for JP-8. With the exception of entrance plate thickness which was varied from 0.090 to 0.375 in., all test variables used in this test series are identical to those used in the standard test series. Initial fuel

temperature was maintained at 95 ± 5°F and ullage pressure at atmospheric pressure. Test results are summarized in Table VIII and mean values of $\Delta P/P_I$ along with ± standard deviations are plotted against the entrance plate thickness in Figure 16.

Inspection of data given in Table VIII shows that both ignition and reaction over-pressures do not vary appreciably with the varying entrance plate thickness.

f. Effects of Venting (Nonequilibrium Ullage)

This series of tests was conducted to determine effects of venting on ignition and reaction over-pressures for JP-8 and propane. For tests conducted with JP-8, test variables with the exception of venting were identical to those used in the standard test series. Vent size was varied from 1 in. I.D. to 4 in. I.D. and fuel temperature was maintained at 95 ± 5°F. For tests conducted with propane, propane was mixed with air at atmospheric pressure to provide 4.2 percent by volume. Results of tests are summarized in Table IX and mean values of $\Delta P/P_I$ along with ± standard deviation are plotted as a function of vent area in Figure 17.

Inspection of data given in Table IX shows that addition of vents has no effect on ignition for both JP-8 and propane. This was expected since addition of vents did not alter any factors governing both fuel spray and incendiary activation. Addition of vents, however, was expected to decrease maximum reaction over-pressures by relieving unburned fuel vapors as well as reaction pressures. Although it was observed that increasing vent size did decrease the maximum reaction over-pressures, the decrease was not as great as was expected. The mean $\Delta P/P_I$ obtained from tests conducted with a 2 in. vent is only 10 to 12 percent lower than that of tests conducted without a vent, and only 30 to 40 percent lower with the 4 in. vent. This is probably due to the high rate of pressure rise associated with gunfire induced fuel-air reactions.

TABLE VIII

EFFECTS OF ENTRANCE PLATE THICKNESS ON
IGNITION AND REACTION OVER-PRESSURE - JP-8

Entrance Plate Thickness, Inches	Number of Tests	Number of Ignitions	Mean ($\Delta P/P_I$)	Standard Deviation
.090	6	6	1.977	.2522
.125	17	14	2.129	.3219
.180	5	5	2.264	.2219
.250	5	3	2.173	.4002
.375	5	5	2.054	.2515

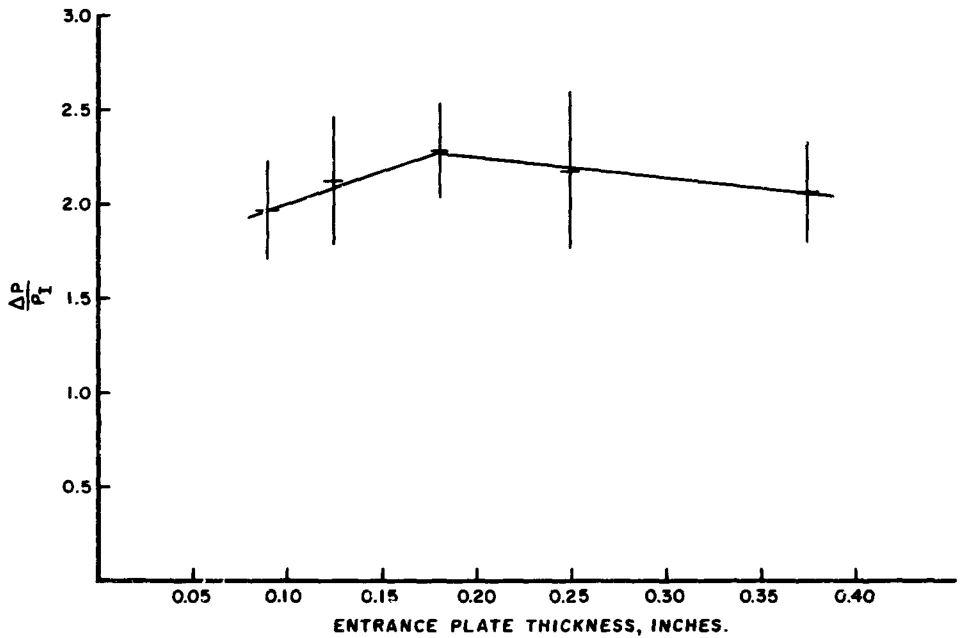

Figure 16. Effect of Entrance Plate Thickness on Reaction Over-Pressure in Tests Conducted with JP-8 at Four-Inch Fuel Depth, 95 ± 5°F, and Atmospheric Ullage Pressure (92-Gallon Tank)

TABLE IX

EFFECTS OF VENT AREA ON IGNITION
AND REACTION OVER-PRESSURE, PROPANE, AND JP-8

	Vent Area Sq. Inches	Number of Tests	Number of Ignitions	Mean ($\Delta P/P_I$)	Standard Deviation
JP-8	0	17	14	2.129	.3219
	.785	5	5	1.996	.2684
	3.141	5	5	1.894	.1868
	7.068	5	5	1.532	.1890
	12.566	5	5	1.312	.4568
C_3H_8	0	5	5	6.196	.0767
	.785	5	5	6.100	.2474
	3.141	5	5	5.460	.5677
	7.068	5	5	4.460	.1642
	12.566	5	5	4.266	.4619

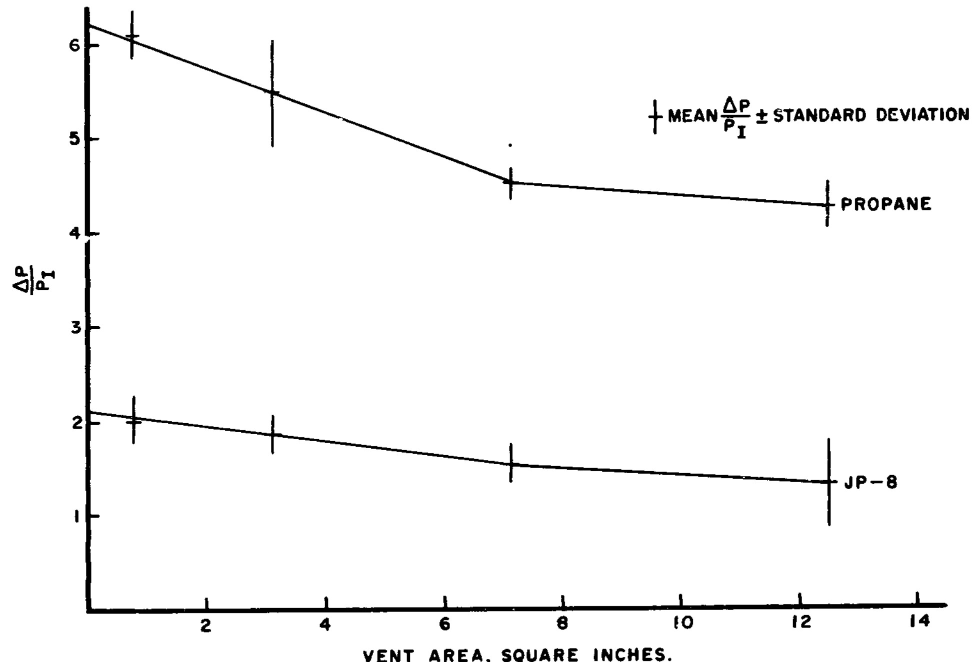

Figure 17. Effect of Vent Area on Reaction Over-Pressure in Tests Conducted with Propane and JP-8; 4.2 Volume Percent Propane-Air Mixtures at Atmospheric Pressure and JP-8 at 95 ± 5°F, Four-Inch Fuel Depth, and Atmospheric Ullage Pressure (92-Gallon Tank)

g. Effects of 14.5 - 113.8 mm API (Nonequilibrium Ullage)

A total of eight tests, four each with JP-8 and JP-4, was conducted to determine effects of Russian 14.5 - 113.8 mm API on ignition and reaction over-pressures. Test variables used in these tests are identical to those used in the standard test series. Initial fuel temperature was maintained at 93 ± 3°F. Results are given in Table X.

When results of these tests are compared with the results obtained in the standard test series, there appear to be no significant differences in results. Thus, on the basis of these eight tests it is concluded that Russian 14.5 - 113.8 mm API and U.S. 50 caliber API rounds are comparable in producing impact-induced fuel-air reaction phenomena.

h. Effects of Jelled JP-8 (Nonequilibrium Ullage)

A total of eight tests was conducted with jelled JP-8 (2 percent Dow Jelling Agent XD-7129.1) over the temperature range of 55 to 80°F. Test variables used are identical to those used in the standard test series. Results are presented in Table XI.

Comparison of results given in Table XI with the results of JP-8 tests conducted in the standard test series shows that reaction overpressures obtained with the jelled JP-8 are slightly higher than those of neat JP-8. However, in view of the fact that there exists a large variation in observed reaction over-pressures such differences cannot be considered significant. Thus, on the basis of these eight tests, it is concluded that under the vertical impact conditions, jelled JP-8 behaves similarly to neat JP-8.

i. Effects of "Whiffle" Balls (Equilibrium Ullage)

This series of tests was conducted to determine effects of "whiffle" balls on ignition and reaction over-pressures for JP-8 and JP-4. For these tests, the test tank (92 gallon capacity) was completely packed with mixed balls consisting of practice golf balls and 1 in. diameter perforated

TABLE X

RESULTS FROM TESTS CONDUCTED WITH 14.5 MM API ROUNDS

Fuel Type	Test Number	Fuel Temp. °F	Fuel Depth Inches	Initial Pressure psia	$(\Delta P)_p$ psi
JP-8	547	90	3.4	14.40	30
"	548	94	3.7	14.40	0
"	549	93	3.7	14.40	24
"	550	92	3.7	14.40	0
JP-4	551	92	4.0	14.40	60
"	552	90	3.7	14.40	57
"	553	92	3.3	14.40	33
"	554	91	4.0	14.40	60

TABLE XI

JELLED JP-8 (2 PER CENT DOW JELLING AGENT, XD-7129.1) TEST RESULTS

Test Number	Fuel Temp. °F	Fuel Depth Inches	Initial Pressure psia	$(\Delta P)_P$ psi
329	55	4.0	14.44	0
330	80	3.7	14.44	47
331	74	3.9	14.44	41
332	69	4.0	14.44	34
333	67	3.9	14.43	33
334	69	4.1	14.43	0
335	73	3.9	14.43	0
336	72	4.1	14.43	45

hollow balls in approximately equal proportion by volume. Each practice golf ball has an outside diameter of 1 3/4 in. with 13 performations approximately 0.20 in. in diameter. Each 1 in. diameter hollow ball is made from high-density polyethylene with a nominal wall thickness of 0.10 in. and 34 uniformly spaced performations 0.060 in. in diameter (Reference 6). Fuel to be tested was circulated by using a spraying bar through the ullage (filled with "whiffle" balls) to produce equilibrium fuel-air mixture. All other test variables used in this test series are identical to those used in the standard test series. Initial fuel temperatures were 86 to 97°F for JP-8 and 18 to 57°F for JP-4. In addition to tests conducted with atmospheric ullage pressure, tests were also conducted with 2-atmosphere ullage pressure. Because of these initial temperature-pressure conditions, the ullage fuel-air mixtures were nonflammable (fuel-lean) for all JP-8 tests and flammable for JP-4. Results of these tests are presented in Table XII.

In tests conducted with JP-8 at 1-atmosphere ullage pressure, the reaction over-pressures ranged from only 1 to 2.5 psi, which is well below the reaction observed in tests conducted under similar conditions but without "whiffle" balls. And in tests conducted with 2-atmosphere ullage pressure, only one of the five tests resulted in ignition. The reaction over-pressure from this test shot is merely 1 psi. These results can be attributed to partial suppression of impact-produced fuel mists and sprays, thus limiting fuel-air reactions within the impacted region of the ullage. No flame propagation beyond this region was observed. Results of these tests are very significant in that the reaction over-pressures are well within the pressure limit of operational aircraft fuel tanks.

In tests conducted with JP-4 at both 1 and 2-atmosphere ullage pressures, a significant reduction in reaction over-pressures was also observed. In 1-atmosphere tests, the reaction over-pressures ranged from 3 to 24 psi, and 2 to 49 psi in two-atmosphere tests. This reduction in reaction over-pressures is probably due to combined effects of reduced fuel mists and sprays, partial quenching of flame, and cooling of combustion products by "whiffle" balls.

TABLE XII

EFFECTS OF "WHIFFLE BALLS" ON IGNITION AND REACTION OVER-PRESSURE

Fuel Type	Test Number	Fuel Temp. °F	Fuel Depth Inches	Initial Pressure	$(\Delta P)_p$ psi
JP-8	423	86	4.3	14.4	0
	424	90	4.1	"	2.5
	425	92	4.2	"	2.0
	426	87	4.2	"	0
	427	90	4.1	"	1.0
	428	93	4.6	29.4	1.0
	429	91	4.3	29.3	0
	430	96	4.1	29.5	0
	431	97	3.9	29.6	0
	432	95	4.0	29.6	0
JP-4	433	22	4.1	14.4	0
	434	18	3.9	"	10
	435	25	3.9	"	3
	436	24	3.9	"	0
	437	39	4.1	"	0
	442	57	4.0	"	24
	438	43	3.9	29.5	49
	439	56	4.0	29.5	38
	440	40	4.0	29.4	2
	441	41	4.0	29.5	35

2. RECTANGULAR TANK

This series of tests was conducted with various rectangular tank configurations defined in Figure 10 as Configurations A, B, C, D, and E to determine effects of fuel-air mass ratios of initial ullage fuel-air mixtures on ignition and reaction over-pressure. Test parameters used in this test series are essentially the same as those used in the standard test series of the cylindrical tank; namely, they are: 50 caliber API rounds fired at approximate service velocity of 2800 ft/sec., 2024 T-3 aluminum for entrance and exit plates with respective thicknesses of 0.125 in. and 0.090 in., and 4 in. of fuel depth. Impact angle was changed from 90° of cylindrical tank tests to 60°; this change was made to insure a proper functioning of incendiary rounds within the reduced ullage height of the rectangular tanks. Fuel to be tested was circulated internally to produce equilibrium ullage fuel-air mixtures and fuel-air mass ratios were varied by either varying fuel temperature or ullage pressure.

Results of tests are given in Tables XIII through XVII. Symbols used in these tables are defined as follows:

T_f	equilibrium fuel temperature in °F
P_f	equilibrium fuel vapor pressure in psi (calculated by using the method outlined in Appendix I)
M_f	average molecular weight of fuel vapor (calculated by using the method outlined in the Appendix)
P_I	initial ullage pressure in psia
F/A	fuel-air mass ratio
$\Delta P/P_I$	ratio of reaction over-pressure to initial ullage pressure
t_P	duration of time in milliseconds from impact to maximum reaction over-pressure (defined in Figure 18)
$(\Delta P/\Delta t)_I$	initial pressure rise rate in psi per millisecond (defined in Figure 18)

TABLE XIII

RESULTS OF TESTS CONDUCTED WITH RECTANGULAR TANK
CONFIGURATION A

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_p	$(\Delta P/\Delta t)_I$
613	JP-8	18	.0063	112.6	14.1	.0017	3.40	111	.70
614	"	19	.0066	112.7	14.1	.0018	3.55	110	.80
615	"	20	.007	112.8	14.1	.0019	2.91	138	.57
632	"	50	.023	114.5	14.5	.0062	3.31	102	.87
633	"	52	.025	114.6	14.5	.0068	3.03	114	.70
634	"	63	.0[illegible]	115.2	14.5	.0096	3.03	116	.84
635	"	65	.037	115.3	14.5	.0101	2.90	110	.63
648	"	76	.053	115.9	14.5	.0146	3.03	95	.80
637	"	102	.116	117.4	14.2	.0333	2.89	71	1.55
640	"	104	.122	117.5	14.2	.0351	3.24	72	1.73
638	"	110	.144	117.8	14.2	.0416	3.24	61	2.40
644	"	113	.155	118.0	14.5	.0440	3.38	63	1.90
641	"	115	.164	118.1	14.2	.0476	2.47	67	1.27
646	"	119	.183	118.3	14.5	.0522	3.03	62	1.80
610	"	18	.0063	112.6	14.1	.0017	0	—	—
612	"	18	.0063	112.6	14.1	.0017	0	—	—
630	"	31	.011	113.4	14.5	.0030	0	—	—
631	"	32	.012	113.5	14.5	.0032	0	—	—
636	"	79	.058	116.0	14.2	.0164	0	—	—
639	"	108	.136	117.6	14.2	.0392	0	—	—
645	"	129	.240	118.9	14.5	.0691	0	—	—
647	"	90	.083	116.7	29.5	.0133	3.05	100	1.60

TABLE XIII (CONT)

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_p	$(\Delta P/\Delta t)_I$
643	JP-8	110	.144	117.8	29.5	.0199	3.12	94	1.46
642	"	106	.13	117.5	29.8	.0177	0	—	—
617	JP-4	10	.29	72.8	14.3	.0520	3.85	73	2.50
625	"	18	.36	73.2	14.5	.0643	3.79	56	2.30
628	"	34	.55	74.2	14.5	.1010	3.31	98	2.40
616	"	10	.29	72.8	14.2	.0524	0	—	—
618	"	11	.30	73.0	14.3	.0540	0	—	—
619	"	26	.45	73.7	14.3	.0827	0	—	—
629	"	35	.56	74.2	14.5	.1029	0	—	—
627	"	36	.58	74.3	14.5	.1069	0	—	—
620	"	40	.64	74.5	14.6	.1179	0	—	—
622	"	40	.64	74.5	14.6	.1179	0	—	—
621	"	41	.66	74.5	14.6	.1218	0	—	—
623	"	41	.66	74.5	14.6	.1218	0	—	—
624	"	41	.66	74.5	14.6	.1218	0	—	—
651	"	75	1.44	76.5	14.4	.2936	0	—	—
653	"	78	1.53	76.6	14.4	.3141	0	—	—
649	"	95	2.20	77.5	14.4	.4827	0	—	—
655	"	48	.78	75.0	29.5	.0703	3.80*	—	3.00
656	"	54	.91	75.3	29.5	.0827	4.27*	—	3.80
657	"	67	1.21	76.0	29.5	.1122	0	—	—
652	"	82	1.69	76.8	29.5	.1612	0	—	—
650	"	86	1.82	77.0	29.5	.1748	0	—	—

*Exit plate ruptured

TABLE XIV

RESULTS OF TESTS CONDUCTED WITH RECTANGULAR TANK CONFIGURATION B

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_P	$(\Delta P/\Delta t)_I$
674	JP-8	75	.052	115.8	14.3	.0145	2.31	90	.90
676	"	115	.164	118.0	14.3	.0472	2.73	264	.93
680	"	30	.010	113.4	14.3	.0027	0	—	—
681	"	30	.010	113.4	14.3	.0027	0	—	—
682	"	30	.010	113.4	14.3	.0027	0	—	—
671	"	36	.014	113.6	14.2	.0038	0	—	—
670	"	37	.014	113.7	14.2	.0039	0	—	—
669	"	43	.018	114.0	14.2	.0049	0	—	—
684	"	63	.035	115.2	14.3	.0097	0	—	—
679	"	73	.048	115.7	14.4	.0133	0	—	—
672	"	78	.056	116.0	14.3	.0157	0	—	—
673	"	78	.056	116.0	14.3	.0157	0	—	—
678	"	86	.073	116.5	14.4	.0205	0	—	—
683	"	33	.012	113.5	29.5	.0016	2.54	893	.87
675	"	75	.052	115.8	29.5	.0070	1.90	177	.75
677	"	104	.122	117.5	29.5	.0168	2.03	933	.80
660	JP-4	31	.51	74.0	14.5	.0931	2.69	192	.85
658	"	30	.50	74.0	14.5	.0912	0	—	—
659	"	30	.50	74.0	14.5	.0912	0	—	—
662	"	39	.62	74.5	14.3	.1166	0	—	—
663	"	40	.64	74.5	14.5	.1188	0	—	—
668	"	42	.67	74.6	14.5	.1248	0	—	—
661	"	31	.51	74.0	29.5	.0449	0	—	—
665	"	68	1.23	76.0	29.6	.1138	0	—	—
667	"	73	1.38	76.3	29.5	1293	0	—	—
666	"	79	1.57	76.6	29.5	.1487	0	—	—

TABLE XV

RESULTS OF TESTS CONDUCTED WITH RECTANGULAR TANK
CONFIGURATION C

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_p	$(\Delta P/\Delta t)_I$
685	JP-8	46	.020	114.2	14.3	.0055	1.61	718	.36
689	"	76	.053	115.9	14.3	.0148	1.75	710	.40
691	"	92	.088	116.8	14.3	.0249	0	—	—
690	"	98	.104	117.1	14.3	.0296	0	—	—
695	"	102	.116	117.4	14.3	.0331	0	—	—
694	"	121	.193	118.5	14.3	.0560	0	—	—
693	"	91	.086	116.7	29.5	.0117	2.31	747	.93
696	"	102	.116	117.4	29.5	.0160	2.17	860	.60
686	"	48	.022	114.4	29.5	.0028	0	—	—
687	"	48	.022	114.4	29.5	.0028	0	—	—
688	"	50	.023	114.5	29.5	.0030	0	—	—
692	"	86	.073	116.5	29.5	.0099	0	—	—

TABLE XVI

RESULTS OF TESTS CONDUCTED WITH RECTANGULAR TANK CONFIGURATION D

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_P	$(\Delta P/\Delta t)_I$
723	JP-8	33	.012	113.5	29.5	.0016	2.51	1230	.37
727	"	74	.050	115.8	29.6	.0067	2.37	1709	.47
726	"	82	.064	116.2	29.6	.0086	2.57	1099	.70
725	"	91	.086	116.7	29.5	.0117	2.51	1441	.53
724	"	104	.122	117.5	29.5	.0168	2.64	1127	.65
720	"	26	.009	113.0	29.5	.0012	0	—	—
721	"	27	.010	113.7	29.5	.0012	0	—	—
722	"	28	.011	113.2	29.5	.0013	0	—	—
713	JP-4	18	.36	73.2	29.5	.0312	3.59	832	1.10
719	"	53	.88	75.2	29.5	.0798	5.29*	—	—
714	"	21	.39	73.5	29.5	.0340	0	—	—
718	"	59	1.02	75.5	29.5	.0940	0	—	—
717	"	63	1.12	75.7	29.4	.1043	0	—	—
716	"	71	1.32	76.2	29.4	.1245	0	—	—
715	"	80	1.60	77.1	29.6	.1521	0	—	—

*Exit plate ruptured

TABLE XVII

RESULTS OF TESTS CONDUCTED WITH RECTANGULAR TANK
CONFIGURATION E

Test Number	Fuel	T_F	P_F	M_F	P_I	F/A	$\Delta P/P_I$	t_p	$(\Delta P/\Delta t)_I$
702	JP-8	86	.073	116.5	29.5	.0099	2.85	80	1.81
703	"	91	.086	116.7	29.5	.0117	2.44	70	1.92
701	"	93	.091	116.9	29.5	.0124	2.41	80	1.80
704	"	26	.009	113.0	29.4	.0012	0	–	–
705	"	26	.009	113.0	29.4	.0012	0	–	–
706	"	27	.010	113.1	29.5	.0012	0	–	–
697	"	36	.014	113.6	29.5	.0018	0	–	–
698	"	37	.014	113.7	29.5	.0019	0	–	–
699	"	38	.015	113.7	29.5	.0019	0	–	–
700	"	100	.114	117.3	29.5	.0158	0	–	–
707	JP-4	27	.46	73.7	29.6	.0401	0	–	–
708	"	27	.46	73.7	29.5	.0403	0	–	–
712	"	64	1.14	76.4	29.5	.1060	0	–	–
711	"	69	1.26	76.5	29.4	.1183	0	–	–
709	"	83	1.70	77.4	29.5	.1634	0	–	–
710	"	86	1.82	77.5	29.5	.1760	0	–	–

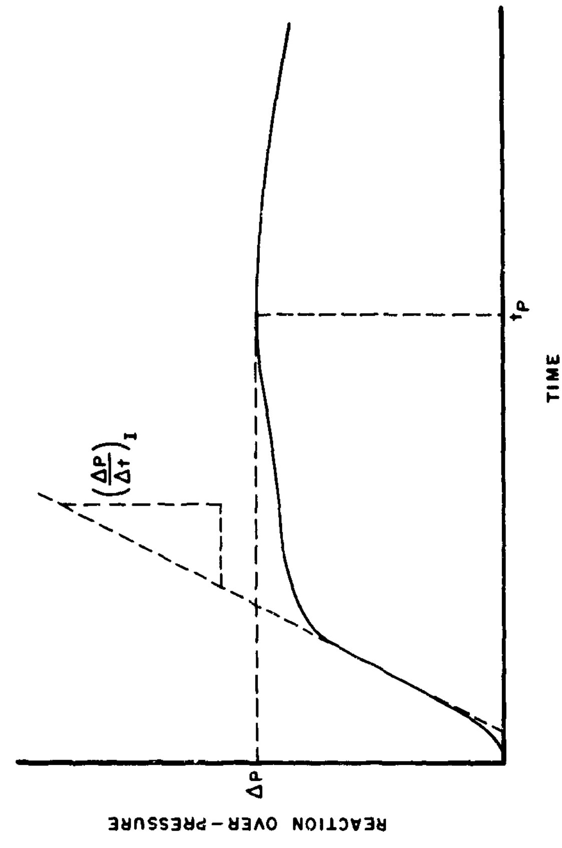

Figure 18. Time-to-Peak Reaction Pressure and Initial Reaction Over-Pressure Rise Rate for a Typical JP-8 Pressure-Time Profile

Inspection of data shows the following results to be evident. The fuel-air mass ratio corresponding to the lower limit of flammability is extended to well below its normal value of 0.03; the fuel-air mass ratio corresponding to the upper limit of flammability is significantly reduced from its normal value of 0.28.

a. Effects of Initial Fuel-Air Mass Ratios on Ignition

In presenting the summary of ignition results involving various rectangular tank configurations in Table XVIII, JP-4 and JP-8 data were pooled in terms of fuel-air mass ratios (F/A) of initial ullage fuel-air mixtures. Pooling of the data is justified since equilibrium flammability characteristics of both JP-4 and JP-8 are expected to behave similarly over a given range of fuel-air mass ratios. From both JP-4 and JP-8, fuel-air mixtures with fuel-air mass ratios in the range of 0.03 to 0.28 are normally considered flammable and fuel-air mixtures with fuel-air mass ratios outside this range nonflammable.

Data obtained from tests conducted with initial fuel-air mass ratios ranging from 0.002 to 0.28 indicate that fuel-air mixtures with fuel-air mass ratios greater than 0.11 could not be ignited. A total of 19 tests was conducted with initial fuel-air mixtures ranging in fuel-air mass ratios from 0.11 to 0.18, and although it was observed that incendiary rounds were properly functioned in all 19 tests, none of these tests resulted in ignition. Of 19 tests, 13 were conducted with fuel-air mass ratios between 0.11 and 0.13, which is approximately one-half of the fuel-air mass ratio corresponding to the normal upper limit of flammability. Thus, it is evident that under the conditions employed in this test series the normal upper limit of flammability is significantly depressed. This behavior of depressing the upper limit of flammability can be attributed to the impact-produced fuel mists and sprays. Addition of fuel mists and vapors to the initially flammable fuel-air mixtures of fuel-air ratio greater than 0.11 evidently leads to fuel over-rich conditions for ignition.

TABLE XVIII

SUMMARY OF IGNITION INVOLVING VARIOUS RECTANGULAR TANK CONFIGURATIONS

Tank Configuration	F/A<.03		.03<F/A<.11		.11<F/A<.28	
	No. of tests	No. of ignitions	No. of tests	No. of ignitions	No. of tests	No. of ignitions
A	16	10	18	11	8	0
B	15	4	5	2	6	0
C	10	4	2	0	None	Tested
D	8	5	5	2	2	0
E	10	3	3	0	3	0

As noted in Table XVIII, tests conducted with initially nonflammable ullage fuel-air mixtures of fuel-air mass ratio less than 0.03 showed that fuel-air mixtures with fuel-air mass ratio as low as 0.002 can be ignited. This result is comparable to that observed in tests conducted with nonequilibrium fuel-air mixtures of the cylindrical tank and, as before, can be attributed to the impact-produced fuel mists and sprays. The percentage of tests resulting in ignition is quite different for different tank configurations and varied from the low value of 26.7 percent with tank configuration B to the high value of 62.5 percent with tank configuration A. Although no apparent reason for these differences can be found, it is evident that smaller tank volume (configuration A) presents the most severe ignition hazard. Results of this series of tests also showed that unless specific measures were taken to suppress fuel mists and sprays the lower limit of flammability cannot be used in assessing potential hazards associated with aircraft fuel tank explosion.

In attempt to determine effects of initially flammable ullage fuel-air mixtures of fuel-air mass ratio ranging from 0.03 to 0.11 on ignition, a total of 18 tests was conducted with tank configuration A. Results of these tests indicated that the percentage of tests resulting in ignition is essentially the same as that of nonflammable fuel-lean fuel-air mixtures. This suggests that for tank configuration A, fuel mists and sprays are the primary factors governing ignition. Because of the limited number of tests conducted with tank configurations B, C, D, and E no meaningful conclusion on the effects of initial fuel-air mass ratio on ignition can be made. However, on the basis of available data, it can safely be assumed that there exists no significant difference in ignition between initially flammable and nonflammable (fuel-lean) fuel-air mixtures. Thus, this assumption along with the results of tests conducted with tank configuration A leads us to believe that for a given tank configuration, initial fuel air mixtures are either too fuel-rich to ignite (F/A > 0.11) or equally ignitible (F/A < 0.11). If this result were to be interpreted in terms of equilibrium fuel temperature and atmospheric ullage pressure, the upper temperature limits of flammability for JP-4 and JP-8 are 38°F and 146°F respectively.

b. Effects of Initial Fuel-Air Mass Ratio on Reaction Over-Pressures

Figures 19 to 22 present results of tests conducted with various rectangular tank configurations. Circles and triangles in these figures represent JP-8 and JP-4 data points respectively. For data points represented by dark triangles in Figures 19 and 21, $\Delta P/P_I$ values were computed from reaction over-pressures at which tank exit plates were ruptured. Thus, actual $\Delta P/P_I$ values for these tests could be higher than those indicated in these figures. All tests resulting in a rupture of exit plates were conducted with JP-4 at 2-atmosphere initial ullage pressure and rupture pressures ranged from 126 psig to 170 psig. Figure 23 presents typical pressure-time profile records for tank configurations A and D.

Inspection of Figure 19, which presents results of tests conducted with tank configuration A, shows that reaction over-pressures ($\Delta P/P_I$) are nearly constant over a wide range of fuel-air mass ratios of the initial ullage fuel-air mixtures. The fact that reaction over-pressures associated with initially nonflammable fuel-lean fuel-air mixtures ($F/A < 0.03$) are comparable to those of initially flammable fuel-air mixtures ($F/A > 0.03$) suggests that impact-produced fuel mists and sprays are most significant factors governing reaction over-pressures. The maximum $\Delta P/P_I$ obtained in this series of tests is 4.27, which is approximately one-half of the maximum theoretically possible value. t_p (time to reach peak reaction over-pressure from an initial impact) and $\Delta P/\Delta t)_I$ (initial pressure rise rate) are plotted as a function of initial fuel-air mass ratios in Figures 24 and 25 respectively. These figures show that initially flammable fuel-air mixtures reach peak reaction over-pressures in shorter time and at a faster pressure rise rate than those of initially nonflammable fuel-lean fuel-air mixtures.

As noted in Figure 20, reaction over-pressures obtained from tests conducted with tank configuration B are also nearly constant over the fuel-air mass ratio range of 0.0016 to 0.0931. Reaction over-pressures are lower when compared with those of tank configuration A and ranged

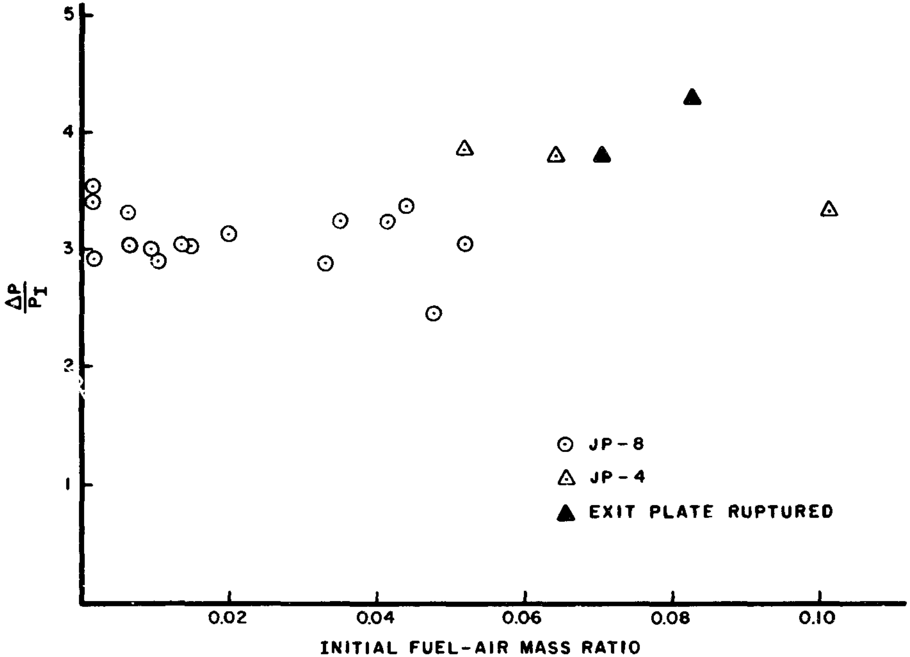

Figure 19. Effect of Fuel-Air Mass Ratio on Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configuration A

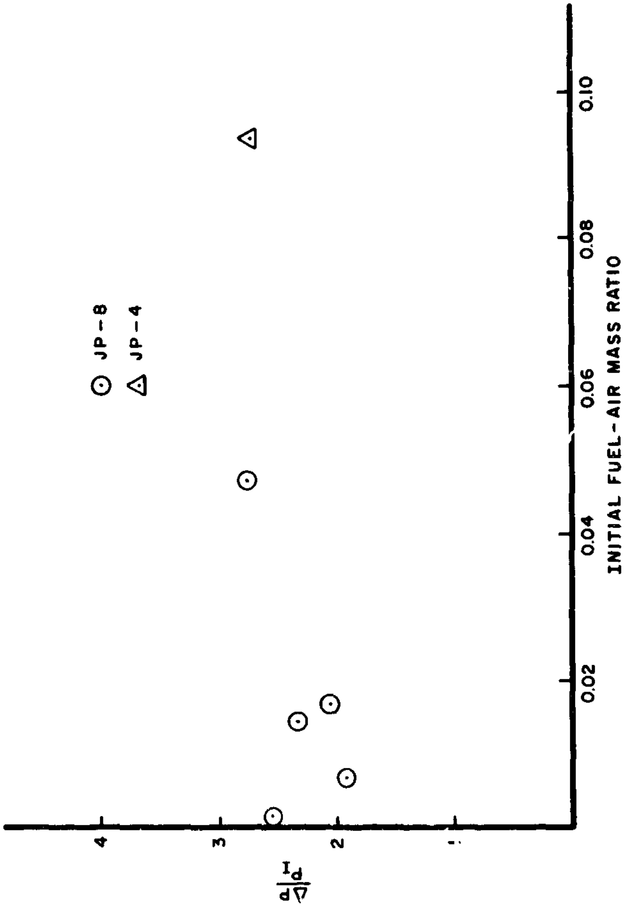

Figure 20. Effect of Fuel-Air Mass Ratio on Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configuration B

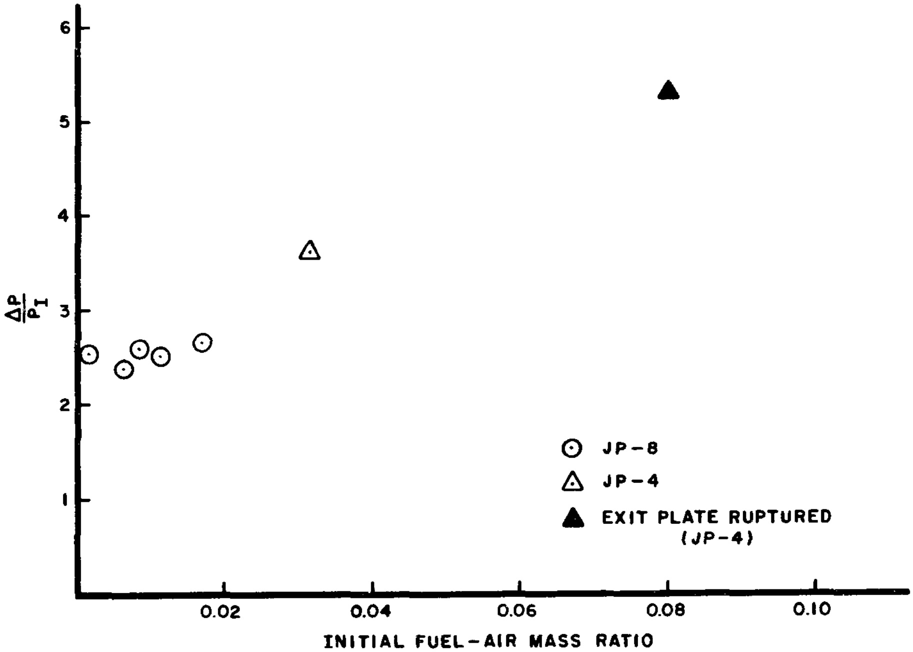

Figure 21. Effect of Fuel-Air Mass Ratio on Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configuration D

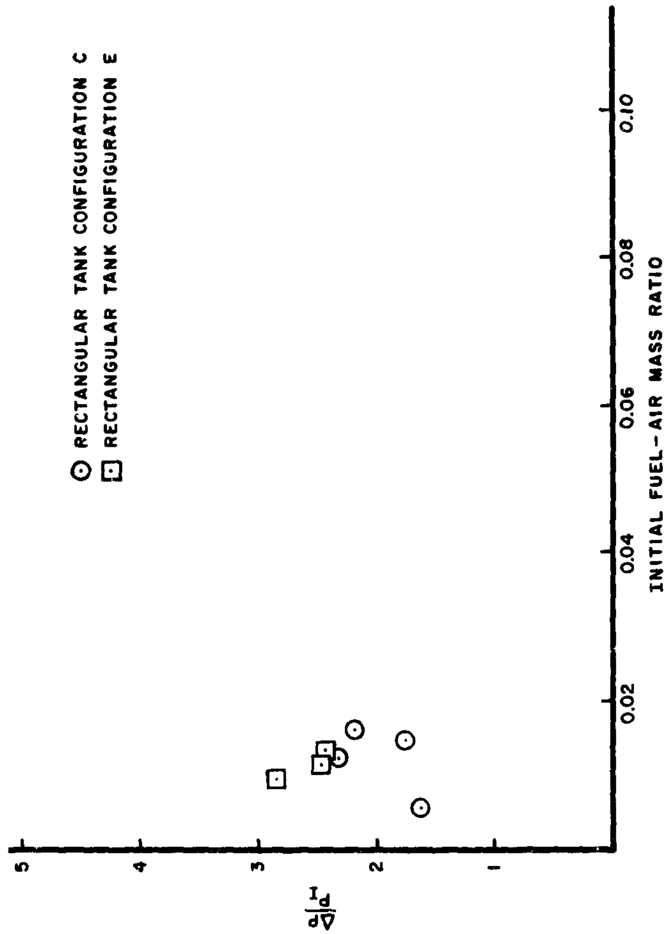

Figure 22. Effect of Fuel-Air Mass Ratio on Reaction Over-Pressure in Tests Conducted with JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configurations C and E

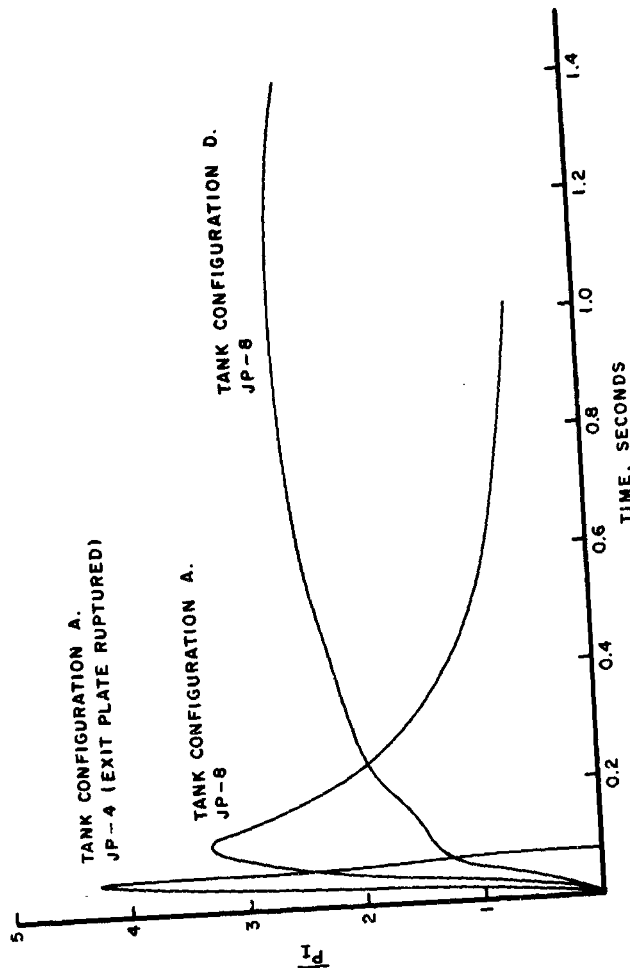

Figure 23. Typical Reaction Over-Pressures in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configurations A and D

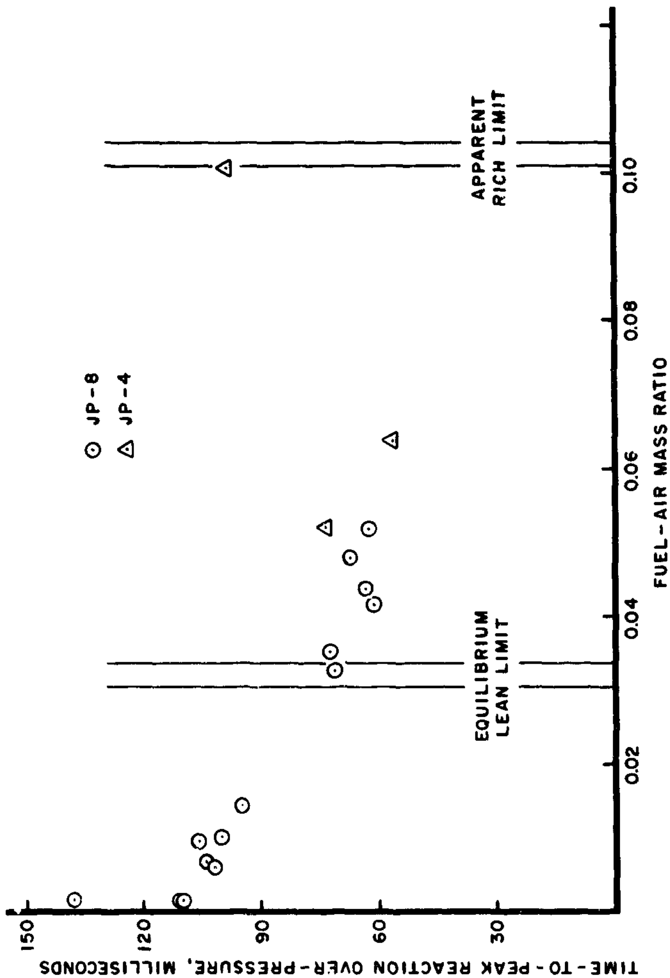

Figure 24. Effect of Fuel-Air Mass Ratio on Time-to-Peak Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configuration A

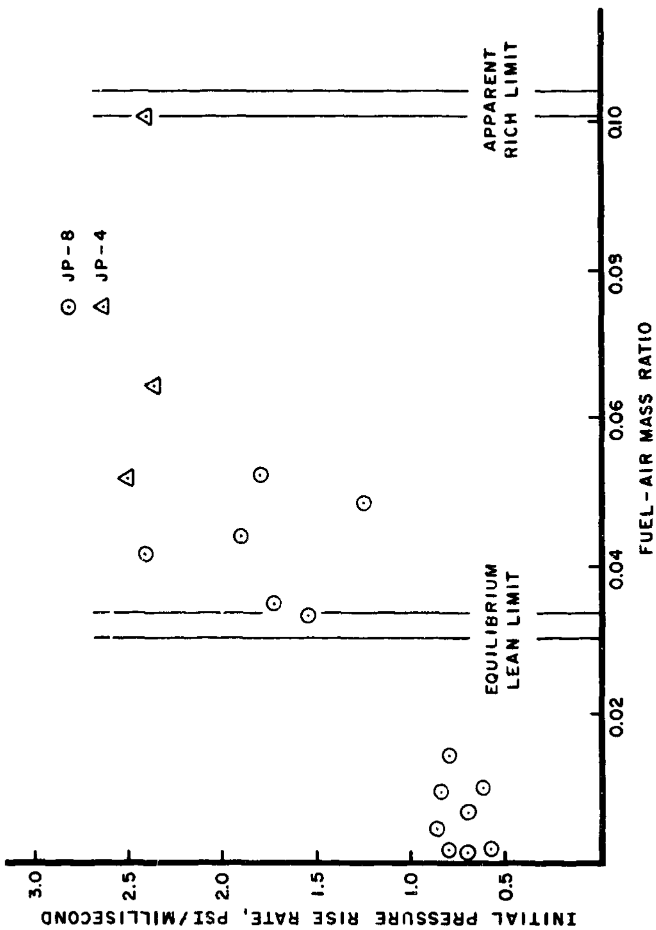

Figure 25. Effect of Fuel-Air Mass Ratio on Initial Pressure-Rise Rate in Tests Conducted with JP-4 and JP-8 at 4-Inch Fuel Depth; Rectangular Tank Configuration A

from the low value of 1.90 to the high value of 2.73. The time to reach peak reaction over-pressure ranged from 90 to 933 milliseconds, and surprisingly, the shortest time is obtained from a test conducted with initially nonflammable fuel-lean fuel-air mixtures. The initial pressure rise rates are nearly constant ranging from 750 to 930 psi/second.

Results of tests conducted with tank configuration D are plotted in Figure 21. Unlike results of tank configurations A and B, reaction over-pressures in this series of tests increased significantly with increased initial fuel-air mass ratio. Reaction over-pressures associated with the initially nonflammable fuel-lean fuel-air mixtures ranged from 2.37 to 2.64; however, when fuel-air mass ratio was increased to .0798, reaction over-pressure increased to 5.29 at which the exit plate ruptured. This increase in reaction over-pressure is probably due to the fact that initial fuel mist-spray reaction near the impacted central region of the tank propagated outward where reaction involved mainly flammable fuel-air vapor mixtures. Thus, for a large tank such as tank configuration D, reaction over-pressures associated with initially flammable fuel-air mixtures are expected to be greater than those of initially fuel-lean fuel-air mixtures. Reaction over-pressures associated with initially flammable fuel-air mixtures reached peak value in shorter time and at faster rise rate than those of initially nonflammable fuel-air mixtures.

Figure 22 presents data obtained with tank configurations C and E. Because of the limited number of tests conducted with these tank configurations, effects of initial fuel-air mass ratio on reaction over-pressure cannot be determined. For tank configuration C, fuel-air mass ratio ranged from .0055 to .0160 with $\Delta P/P_I$ varying from 1.61 to 2.31. t_p and $(\Delta P/\Delta t)_I$ ranged from 710 to 880 milliseconds and 360 to 930 psi/second respectively. For tank configuration E, $\Delta P/P_I$ values given are those obtained from transducers mounted on the center tank (impacted section of three compartmental tanks). $\Delta P/P_I$ values from compartmental tank sections are within 2 to 3 psi of the center tank. Time to reach peak reaction over-pressure and initial pressure rise rate for this tank configuration is similar to those of tank configuration A.

SECTION V

CONCLUSIONS

1. On the basis of results obtained from "nonequilibrium" gunfire tests conducted with the cylindrical tank configuration, the following conclusions are made.

Flammability limits - the upper temperature limit for JP-4 and the lower temperature limit for JP-8 - are significantly extended from those of equilibrium fuel-air vapor mixtures. In tests conducted with JP-8, ignition was observed at fuel temperatures as low as 10°F; and JP-4 was found to be ignitible at fuel temperatures as high as 130°F. Reaction over-pressures associated with JP-8 are generally lower when compared with those of JP-4 over the same temperature range. The mean values of $\Delta P/P_I$ ranged from 1.55 at 10 - 19°F to 2.55 at 120 - 130°F for JP-8 and 1.78 at 30 - 39°F to 3.74 at 70 - 79°F for JP-4.

Increasing initial ullage pressures from 1-atmosphere to 2-atmospheres resulted in a slight increase in reaction over-pressures for JP-8 and a significant increase for JP-4. All tests conducted with JP-4 resulted in a rupture of exit plates. Rupture pressures ranged from 85 to 108 psi. These pressures are two to three times higher than those of JP-8 tests conducted under similar conditions.

For JP-8, increasing fuel depth from 2 to 12 inches has no significant effect on ignition; however, at 14 and 16 inches of fuel depth, ignition percentage is significantly reduced. Mean values of $\Delta P/P_I$ tend to decrease with increasing fuel depth The mean $\Delta P/P_I$ ranged from 2.13 at 4 inches of fuel depth to 1.11 at 16 inches of fuel depth. For JP-4, increasing fuel depth has an effect of reducing ignition percentage. This reduction in ignition is attributed to increased fuel vapor concentration.

Increasing the tank volume from 92 to 185 gallons has no significant effect on ignition for both JP-8 and JP-4. However, the increased tank

volume resulted in a significant reduction in $\Delta P/P_I$ for JP-8 and an increase for JP-4. Tests conducted with initial ullage pressures of 1-atmosphere showed that the mean $\Delta P/P_I$ ranged from .806 to 1.033 for JP-8 and 3.910 to 4.110 for JP-4 over the same fuel temperature range. From tests conducted with 2-atmosphere ullage pressures, mean $\Delta P/P_I$ ranged from .568 to 1.130 for JP-8, and for JP-4, all tests resulted in a rupture of exit plates. Thus, for large tanks, JP-8 appears to be more safe when compared to JP-4.

Increasing entrance plate thickness from .090 to .375 inches has no significant effect on both ignition and reaction over-pressures.

Increasing venting area from no vent to 12.566 square inches has no effect on ignition but significantly reduced reaction over-pressures. The mean $\Delta P/P_I$ ranged from 2.129 at no vent to 1.312 at 12.566 square inches of venting area for JP-8 while for stoichiometric propane mixtures, it ranged from 6.196 to 4.266.

A limited number of tests conducted with jelled JP-8 (2 percent Dow Jelling Agent XD-7129.1) over the temperature range of 55 to 80°F showed that jelled JP-8 behaves similarly when compared with neat JP-8.

Results of tests involving tanks fully packed with "Whiffle" balls showed that both ignition and reaction over-pressures are significantly reduced when compared with tests conducted under similar conditions but without "whiffle" balls. For JP-8, reaction over-pressures ranged from 1 to 2.5 psi at initial ullage pressure of 1 atmosphere and 1 psi at 2 atmospheres. Results of these tests are very significant in that the reaction over-pressures are well within the pressure limit of operational aircraft fuel tanks. For JP-4, reaction over-pressures ranged from 3 to 24 psi at initial ullage pressure of 1 atmosphere and 2 to 49 psi at 2-atmospheres initial ullage pressure.

2. The following conclusions are made on the basis of equilibrium tests conducted with various rectangular tank configurations.

The lower limit of flammability is significantly extended from that of equilibrium fuel-air vapor mixtures. Ignition was observed in fuel-air mixtures with fuel-air mass ratio as low as 0.002. This result is similar to that of nonequilibrium tests of the cylindrical tank.

The upper limit of flammability is significantly depressed when compared with that of equilibrium fuel-air vapor mixtures. Fuel-air mixtures with initial fuel-air mass ratio greater than 0.11 could not be ignited. If this result were to be interpreted in terms of equilibrium fuel temperature and atmospheric ullage pressure, the upper temperature limit of flammability for JP-4 and JP-8 are 38°F and 146°F respectively. Thus, in terms of ignition, JP-8 is vulnerable over a wider temperature range than JP-4. However, it should be noted that unless strict measures were taken to assure ullage equilibrium conditions at all times the upper temperature limit of flammability cannot be used in assessing potential hazards associated with gunfire induced explosion.

The percentage of tests resulting in ignition below the initial fuel-air mass ratio of 0.11 appears to be strongly dependent on tank configurations; tank configuration A (smallest tank volume) produced the most severe ignition hazard with approximately 62 percent of tests resulting in ignition.

For small tanks (configurations A and B), reaction over-pressures are nearly independent of initial fuel-air mass ratios. For a large tank (configuration D), reaction over-pressures resulting from initially flammable fuel-air mixtures ($F/A > 0.03$) are much higher than those of nonflammable fuel-air mixtures ($F/A < 0.03$).

Reaction over-pressures resulting from tests conducted with tank configuration A are generally higher than those of any other tank configurations.

Tests conducted with a compartmented tank (configuration E) showed that reaction over-pressures measured from compartmented sections are 2 to 3 psi higher than that of center section (impacted section of the three-compartment tank).

APPENDIX

VAPOR PRESSURES AND AVERAGE MOLECULAR WEIGHTS OF EQUILIBRIUM FUEL VAPORS FOR JP-4, JP-8 (104°F FLASH POINT), AND JP-8 (116°F FLASH POINT)

Vapor pressures and average molecular weights of equilibrium fuel vapors used in determining fuel-air mass ratios were calculated from ASTM distillation data using the British Petroleum Method. ASTM distillation data for each test fuel was periodically determined as a part of routine fuel test. A typical fuel test report follows. Figures 26 and 27 present calculated results of vapor pressures and average molecular weights of equilibrium fuel vapors.

FUELS TEST REPORT — DATE: 17 March 71

SUBMITTED BY	TEST LABORATORY AND LOCATION	ORIGIN OR CONTRACTOR
G. Gandee	AF Aerospace Fuels Lab SFQLA WPAFB OH	

LABORATORY TEST NUMBER	1757	2788	1756
DATE RECEIVED IN LAB	24 Jun 1969	27 Nov 70	24 Jun 1969
SPECIFICATION NUMBER	56248		83133
GRADE NUMBER	JP-4	JP-8	JP-8
CONTRACT NUMBER			
QUANTITY REPRESENTED (GALS)			
TYPE CONTAINER AND NUMBER	1 gal	1 gal	1 gal
SAMPLE NUMBER		3	
REMARKS (PERTAINING TO SAMPLE AS RECEIVED)	Gun Range		SOHIO M-F-11
LABORATORY DATA			
GRAVITY °A.P.I.	50.4	45.1	43.8
WSIM			
APPEARANCE			
~~COLOR~~ Viscosity @100°F		1.67	
ODOR		7.40	
WATER REACTION			
FREEZING POINT °F	Below -72	Below -51	-65
CORROSION	Negative	Negative	Negative
EXISTENT GUM, MG/100 ML	0.2	0.[illegible]	0.0
POTENTIAL GUM, MG/100 ML		1.2	
OXIDATION PPT MG/100 ML			
DOCTOR TEST	Negative	Negative	Negative
MERCAPTAN SULFUR, % WT	0.0	0.0	0.0
TOTAL SULFUR, % WT	0.010	0.022	0.049
VAPOR PRESSURE P.S.I. @ 100°F	2.6		
ANILINE POINT °F	134.0	147.0	143.0
ANILINE GRAVITY CONSTANT OR B.T.U.	6.754	5.630	6.263
SMOKE POINT MM (OR SMOKE VOL INDEX)	59.2		LIM 51-SP-25
AROMATICS, %	12.1	11.7	15.9
OLEFINS, %	1.0	1.0	2.2
TETRAETHYLLEAD ML GAL			
FLASH POINT, °F		102-104	116
KNOCK RATING	LEAN / RICH	LEAN / RICH	LEAN / RICH
TOTAL SOLIDS, MG/GAL			
FIBROUS MATERIAL PER QT			
VISIBLE FREE WATER ML GAL			
NONCOMBUSTIBLE SOLIDS MG/GAL			
TOTAL WATER PPM BY VOL BY KARL FISCHER			
THERMAL STABILITY TUBE DEPOSIT CODE NO			
THERMAL STABILITY, PRESSURE DIFF (IN. HG)			
MIL-I-27686 ICING INHIBITOR % BY VOL	0.087	0.122	0.068
DISTILLATION IBP °F	123	294	314
10%	214	340	364
20%	270	358	376
40%			
50%	35[illegible]	[illegible]00	404
90%	439	467	461
E PT	467	500	508
REC	98.0	98.0	98.0
RES %		1.0	1.0
LOSS	1.0	1.0	1.0

REMARKS (PERTAINING TO USABILITY AND DISPOSITION OF MATERIAL)

APPROVED BY (NAME AND SIGNATURE OF LAB SUPV)

AFTO FORM SEP 65 68 SUPERSEDES SEP 63 EDITION WHICH WILL BE USED

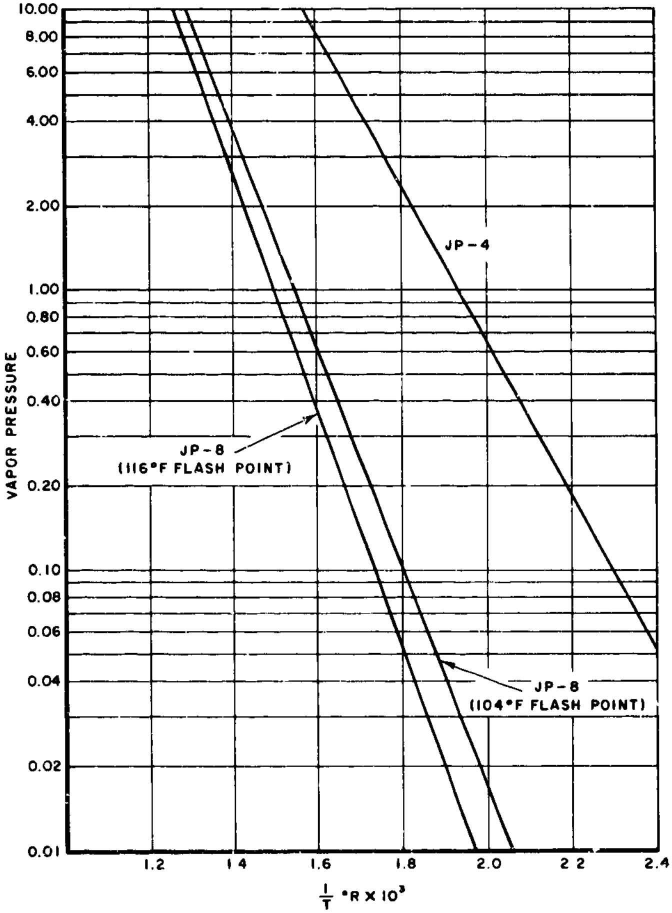

Figure 26. Vapor Pressures Calculated from ASTM Distillation Data Using British Petroleum Method

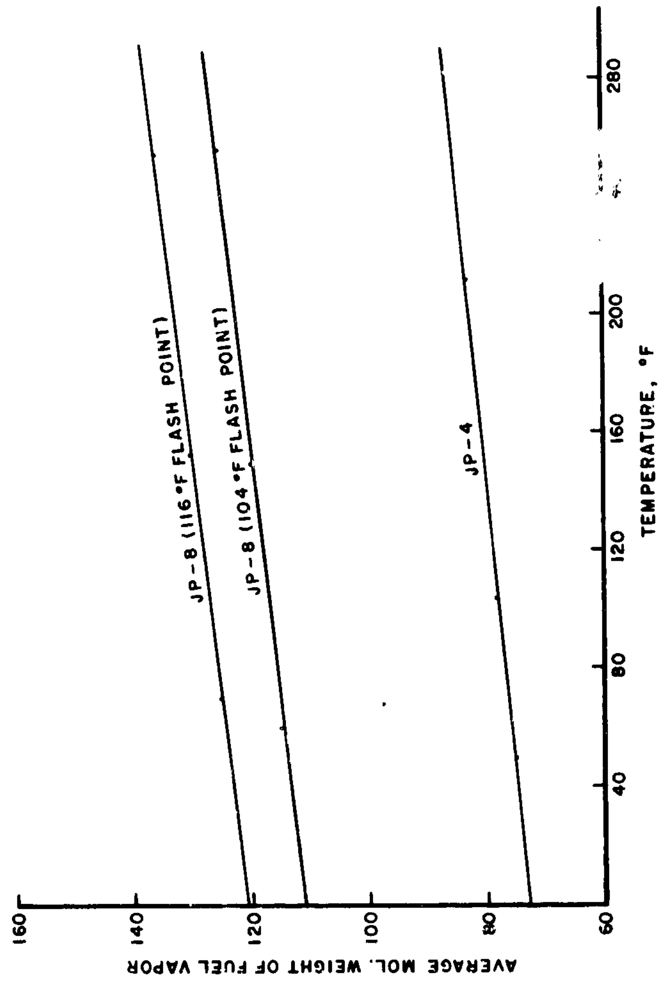

Figure 27. Calculated Average Molecular Weights of Fuel Vapors

BIBLIOGRAPHY

1. Botteri, B. P., Gandee, G. W. and Morrisey, E. J. - Investigation of Perforated Plastic Spheres Concept for Fuel Tank Fire Suppression, Technical Report AFAPL-TR-69-1, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio, April 1969.

2. Jones, G. W., et. al. - Research on the Flammability Characteristics of Aircraft Fuels, WADC-TR-52-35, Supplement 1, Wright Air Development Center, Wright-Patterson AFB, Ohio. January 1954.

3. Kosnic, T. C., Zung, L. B. and Gerstein, M. - Analysis of Aircraft Fuel Tank Fire and Explosion Hazards, Tech. Report AFAPL-TR-71-7, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio March 1971.

4. Ott, E. E. - Effects of Fuel Slosh and Vibration on the Flammability Hazards of Hydrocarbon Turbine Fuels within Aircraft Fuel Tanks, Tech. Report AFAPL-TR-70-65, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio. November 1970.

5. The Calculation of the Vapour Pressures of Aviation Fuels, The British Petroleum Company Limited, BP Research Center, Petroleum Division, Sunbury-On-Thames, Technical Memorandum No. 110.040, June 1960.

6. Zengel, A. E., Lander, H. R. and Warren, J. H. - An Examination of Methods for Calculating Vapor Pressure of Petroleum Hydrocarbon, Tech. Report APL-TDR-64-37, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio. March 1964.